Faculty of Science and Technology

MASTER'S THESIS

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Abstract

Automation is introduced to the industrial field long time ago, but still in its first steps in the oil and gas industry. There are many reasons led to this slow of automation in this industry. These reasons related to the industry itself, technical reasons, and human related reasons.

Manage pressure drilling (MPD) is one of the important and advance drilling methods today to solve a lot of drilling problems in high efficiency, safe and economic way.

The automation drilling based on understanding both automation processes and drilling process in design, planning and execution. The automated MPD expected to be the most efficient method of drilling in the next few years both as a drilling operation and as an automation system.

The automated MPD technology faces many limitations and challenges relating to the complexity of the operation itself, the dynamic variable effects the operation, the data acquisition quality, and the crew skills level. These challenges and limitations are detailed illustrated in this thesis to figure out clearly the requirement to develop this advance technology currently and for the future.

The thesis objective is to suggest a general standard automated MPD structure to cover the MPD applications solving the drilling problems facing the drilling operation in different types of wells. Automation models govern the drilling parameters and gives the ability to switch between different MPD application depending on the well type and the drilling problem.

This thesis discusses the current automation system and the current (MPD) method individually. Then discussing the current automated MPD used through some years ago and discussing its limitations and challenges in four different case studies each relating to a specific drilling problem and specific well situation.

This thesis is a step forward to indicate the basement required to build up such a general standard automated MPD structure.

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Qassim Hameed Majeed

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List of Abbreviations

AFP	Annulus Friction Pressure
APWD	Annular Pressure While Drilling Measurements
BHA	Bottom Hole Assembly
BHP	Bottom Hole Pressure
CBHP	Constant Bottom Hole Pressure
CCS	Continuous Circulation System
CCV	Continuous Circulating Valve
CIV	Casing Isolation Valve
CMC	Controlled Mud Cup
CPU	Central Process Unit
CTR	Cutting Transport Ratio
DAPC	Dynamic Annular Pressure Control
DAS	Data Acquisition System
DBR	Daily Drilling Report
DDV	Downhole Deployment Valve
DIV	Downhole Isolating Valve
DGD	Dual Gradient Drilling
DHAD	Downhole Air Diverter
DHP	Down Hole Pressure
DPPT	Dynamic Pore Pressure Test
DTTL	Drill Thru The Limits
ECD	Equivalent-Circulating Density
ECD-RT	ECD Reduction Tool
ERD	Extended reach drilling
FBD	Function Block Diagram
FIT	Formation Integrity Test
HCV	Hydrostatic Control Valve

HEI	Human Error Identification
HMI	Human machine interface
HPU	Hydraulic Power Unit
HRA	Human Risk Analysis
HTHP	High Temperature High Pressure
IACD	International Association of Drilling Contractors
ICU	Intelligent Control Unit
IL	Instruction List
IO	Integrated Operations
IT	Information Technology
LD	Ladder Diagram
LOT	Leak off Test
LQG/LQR	linear-quadratic-Gaussian regulator
LRRS	Low Riser Returns System
LWD	Logging While Drilling
MCD	Mud Cup Drilling
MFC	Micro Flux Control
MPC	model predictive control
MPD	Managed Pressure Drilling
MW	Mud Weight
MWD	Measurement While Drilling
NPT	Non-Productive time
NRV	Non-return valve
OBM	Oil-Based Mud
PAC	Programmable Automation Controller
PC	Personal Computer
PCWD	Pressure Control While Drilling
PDC bit	Polycrystalline Diamond Compact bit
PID	Proportional - Integral – Derivative

PLC	Programmable Logic Controller
PMCD	Pressurized Mud Cup Drilling
PPT	Pore Pressure Test
QTV	Quick Trip Valve
RCD	Rotating Control Device
RFC	Return Flow Control
ROP	Rate Of Penetration
ROV	Remoted Operated Vehicle
RPM	Revolution per Minute
RSS	Rotary Steerable System
RTU	Remote Terminal Unit
SAC	Secondary Annular Circulation
SAS	Substation Automation System
SBM	Synthetic Based Mud
SBP	Surface Backpressure
SCADA	supervisory control and data acquisition/ Control and Data Acquisition System
SFC	sequential function chart
SMD	Subsea Mud lift Drilling
SPE	Society of Petroleum Engineers
SPP	Standpipe Pressure
ST	Structure Text
TD	True Depth
TVD	True Vertical Depth
UBD	Underbalanced Drilling
WOB	weight on bit
WR_NRV	Wireline Retrievable Non-Return Valve
XML	Extensible Markup Language

Chapter 1

Introduction

1.1 Motivation

As the oil and gas industry looking always to new development and optimization methods to increase profitability, increase efficiency, increase safety, decreasing non-productive time (NPT), and solve the difficult to solve problems especially in drilling operation.

The drilling methods vary according to the well status and in the recent years, conventional drilling method faced many drilling problems that is difficult to reach the well true depth (TD) to start production. These drilling problems such as kick, losing circulation in the formation, narrow drilling widow that makes drilling hard to perform or impossible, high pressure high temperature HPHT wells, high depth wells and so on, that required new technologies of drilling to face such drilling challenges.

Managed pressure drilling methods (MPD) solved many drilling issues such the above mentioned. Later MPD faced some control problems because of the MPD drilling operation sensitivity to pressure, human error and other drilling parameters, so it required automating the drilling process partially or fully.

Automation is a modern technology in oil and gas industry that expected to take a wide space in industry in the next few years. This technology contributed to mitigate and eliminate the downhole drilling problems by using automation control systems in the drilling operations especially in the MPD applications in addition to the rig automation system that have been used as a full automation system with no human on rig.

Automated MPD is the combination of automation methods and MPD applications used since 2003 as a partial automation system. This thesis central subject is the combination of these two important technologies currently and for future, tries to discuss the two technologies individually, and combined. It is important to study these two technologies details enough and study the current level combination of these two technologies in different cases both offshore and onshore to make a clear image for future possibilities for the automation drilling technology generally and in the MPD application especially.

This thesis aim to present the essential elements of automated MPD and its future possible structure image. The image based on currently automated MPD operations and trying to generalize and standardize the automated MPD to be suitable for the most drilling situations in different kind of wells, and the possibility to be general for the entire oil and gas industry in the future.

The technology development always following short steps of development, optimizing, and this thesis trying to introduce a general picture for the future technology of automated MPD to make the forward steps faster and clear. This study may be a good reference for many studies in many aspects related to automation drilling to make it more systematic process that following the drilling problems requirements.

1.2 Scope of thesis

The automated MPD is a modern drilling technology implementing both automation in different levels and MPD different applications and considers as the future drilling method in its fully automated form to provide a completely non-human operation controlled a long away from the rig.

Both automation and MPD is a parameter dependence process that depending on the real time data measurements to be used in all the operation phases (before, during, and after). Automation consist of many aspects such as models, data acquisition systems, data communications, controllers and data simulations all used to perform an automated operation to control the entire operation or the difficult manually controlled elements in any industrial operation. This thesis discussing the automation systems, tools, and related aspects.

The managed pressure drilling includes many drilling methods associated with the well situation and the drilling parameters. This type of drilling is a modern type that came in the need of solving many drilling problems that are hard, costly and unsafe to solve by implementing the conventional drilling method.

Automated MPD begun to use in the start of this century after a long enough study. Implementation of this technology provide high accuracy results, save some NPT costs, and safety. Therefore, the improvement of such technology to meet the drilling requirements and reach the optimum of automation level in the future seems to be a very important issue for the oil and gas industry.

Therefore, in this thesis have being discussed the following aspects:

- Automation review to illustrate how is the automation system works currently and in the future.
- The managed pressure drilling (MPD) review in details
- The automated MPD, cases study and suggestions for the current and future MPD process.
- Discussing the basement of generalizing and standardizing automated MPD to meet all the well types drilling problems and methods.

1.2.1 Contents

Chapter 2 represents drilling automation in general, history of drilling automation, what and why drilling automation, advantages of drilling automation, levels, modeling, data communication, modes of automation, envelope protection automation, closing loop automation, and multi-level control structure.

Chapter 3 represents drilling automation tools such as control systems that include many aspects as following:

- Branches of control systems
  - Real Time modeling and monitoring
  - Human machine interface (HMI)
  - Programmable Logic Controller (PLC)
  - Data Acquisition System (DAS)
  - Sensors used in control systems

- Classical control system

- Modern control system
- The control system design process
- Mathematical models associated with the control system
- MATLAB and SIMULINK as a requirment for control system
- Types of control
- Controller
- Algorithm
- Tuning

Chapter 4 represents modeling in automation and models used for several drilling parameters such as hydraulic model, rheology model, etc. with considering the mathematical background for each model and indicating their effect on the automation process and the drilling operation.

Chapter 5 representing MPD as a theory of drilling and the reason of adopting MPD, the different types of MPD with details for each type, the tools and equipment used in MPD, MPD limitations and challenges and MPD categories.

Chapter 6 representing automated MPD and development including illustration of automated MPD, levels of automated MPD, different cases studies of automated MPD previously made, the general structure of automated MPD, automated MPD limitations and suggestions and a suggested simplifying and generalization of automated MPD.

Chapter 7 representing the thesis conclusion that discussing the current technology and the future technology according to the current technology and the limitations and challenges facing this technology.

Chapter 2

Drilling Automation

2.1 Automation

2.1.1 Introduction (Shields, 2011) (Geehan, 2013) (III, 2007)

According to many references, Automation defined as "A technology dealing with the application of mechatronic and computers for production of goods and services. Automation is broadly classified into manufacturing automation and service automation."

Automation divided into three types fixed automation, programmable automation and flexible automation.

Reasons of implementing automation are:

- Shortage of labor
- High cost of labor
- Increasing productivity
- Lower cost
- Reducing process lead time

There are many definitions of automation addressed in different meanings according to the historical era automation passed through, the technical background it addressed for, and the development effect on automation.

Drilling automation, using engineering for drilling operation by using computer to control and manage the parameters effect the drilling operation such as flow rate, down hole pressure DHP, mud weight MW, pore pressure PP, fracture pressure FP and so on.

It is kind of integration among human, machine and computer because of drilling machinery development, sensor technology, parameters concern drilling scientific researches, control systems, and IT technology.

Automation changes along the time, since it started, divided into three eras: mechanization, semi-automation and local automation. (III, 2007)

Mechanization means replacing labor power by mechanical power that provides more torque and forces as an additional benefit. Semi-automation means to automate some of the mechanical operation and using intelligent labor to feed the automated machines with required data.

While local automations done by transform the semi- automated operation to a completely automated operation with no need to human interface to execute it.

Another definition of automation according to the fast development of technology within the drilling community. Development that related to drilling machinery, sensors technology, control systems, and computer and communications technology. This explosion of technology led and will lead to change in the drilling automation from machine level to full integrated operations. (Fionn Iversen, 2012)

Define and recognize automation as a term or/and as a process level has an importance of identify the operation to be known for different parts related to the oil and gas industry such as contractors, service, and operating companies.

Automation can be defined as replacing human by electronic or/and mechanical devices. This definition, after a while, extended to two concepts. First, to include many processes instead of structural environment such as drilling, and second, describes human labor by two ways physically and mentally. (Fionn Iversen, 2012)

Sheridan (2002), categorized automation in main terminologies:

- Mechanization and sensing integration.
- Data process and decision-making.
- Mechanical and information action.
- Open loop operation on closed control.

Sheridan called the human- automation system that divided into two categories, mechanization and computerization.

Mechanization means replacing human labor by machines that physically operated by human. While computerization means the process operated or controlled by a computer with providing an interface between human and machine.

2.1.2 Automation levels

Automation levels ranging from full manual control to full-automated system and the levels in between have different manual and automation degrees in each level. Some researches consider just one degree that is a completely automated with no interface with the driller/operator.

It could be said that there are three levels of Automation which are fully manual, semi-automated and fully automated.

The semi-automated level may contains the different degrees of manual and automation in the level. The semi-automated system levels two options, decision and action options that the operator/computer has. If the computer has less decision and action options, then the level is close to the manual level, while if the operator has less decision and action options, so the level is close to the automation level.

2.1.3 Modeling (John Thorgood, 2010)

Making a model is a process of using pre-data and real time data. Thus modeling uses the work done and the optimization processes. There are some other parameters affecting real time data and thus affects modeling, such as:

- Functionality type
- Frequency
- Set point
- Reaction time.

The drilling operation today has a functionality that could be classified as an open loop system unless it imitated by a many considerable real time issues to be a closed loop and a true automated operation.

The effecting parameters are:

- Flexible and scalable model accepting additional functionality.
- Data missing
- Limited data transmission bandwidth.
- Diagnostic algorithm effect on bandwidth.
- Modal accuracy estimating under abnormal situations such as missing data.
- Fast set point change under sudden parameters change.
- Physical machine response.

Modeling design based on several structural issues that forming the general concept of modeling, which are:

- Variables/ parameters
- Predicting
- Post analysis
- Relationship
- Controllers
- Fault detection
- Estimations

There are many drilling models today such as Earth seismic model, Drilling optimization model and fluid model that controlling drilling operations such as ROP, cement circulation, tripping, wellbore pressure, drill string vibration, and so on. These models works today independently, but through automation it may be possible to integrate them together as a general drilling automation system based on safety, performance and economics.

Well construction depending on formation behavior analysis that based on information taken from an earlier operations or study reports. This information used to build up the automation models, and any update for the information can be done manually with a recommendation of using an electronic source to ensure a high quality automation.

Remote Support and decision making have a direct and indirect relationship with the drilling procedures and data resolution that used for estimation to help in decision making. This required parameters updating to feedback it to the models for automation optimizing. Time-scale analysis is a central item in parameters updating that helps to decision making of how to manage and update the hole automation system.

Data resolution and response time are an important factors for the well instruction processes. Resolution and delay divided into four groups sub-second, sub-minute, intermediate (minutes), and long (hours).

Sub-second response works in a specific system while the rest of responses work in wider operations.

Resolution and delay have another name, which is control-time, that dealing with resolution and control algorithms to control the drilling operation`s several parameters. Measurement time divided to instantaneous and long time, where long time cannot be used as a feedback in the control algorithm.

2.1.4 Data Communication (Shields, 2011) (John Thorgood, 2010)

Previously, Data used for monitoring that adjusts by operators, and with coming of mechanical drilling, data used for monitoring also, and to plan a drilling program by few companies. Data recovery started with the advent of electronic that make it available from a network connection to be used widely as a planning tool. For automation system, data used with some conditions such as availability, complete and correct.

The short trend operations accepted some data incorrect, but not long trend operations because of effecting the operation performance.

Unconditional data exchange make problems in the system, so it is important to choose the right data exchange by following a standard communication protocol. In general, Protocols and protocol response should follow requirements and data requirements where some of data depict slow changes and other depict quickly changing.

System integration is one of the complicities that facing the automation drilling because of many factors such as:

- Poorness of the information available for the operator about the system.
- Avoiding information overload between the system and the operator specially when connecting multiple services.
- Standard change-management techniques that needs to be initiated which have complicity relating to the process changes magnitude.
- The system security, which is a challenge for the industry because of the miss-communication between different parties (operator, contractor and third part).

Machines and models interface is an important issue for the automation drilling where machines emulate human action to execute a process and with help of real time date form models sensors to update the existing data for the machine action. This type of continuous communication in the system will improve the drilling operation and provide standards of automation to be in touch always with the technological advances.

2.1.5 Modes of automation (Øyvind Breyholtz, 2011)

The classification of automation modes depends on the feature level of the operator and the automation system in every mode. In general, there are three automation modes, fully manual, semi-automated, and fully automated. The semi-automated mode has five modes differentiated from each other by thier responsibility/ feature level for the operator and the automation system for each mode. The total are seven modes explained as followed refers to Thorogood et al. (2009) and Ornaes (2010):

- Level 0: Direct manual control; completely operator decision making depends on presented raw signals and alarms.
- Level 1: Assisted manual control; where the operator assisted by an automation system that analyzing the current information of the well and present it to the operator.

- Level 2: Shared control; where using envelope protection philosophy in this level that means the automation system has interfering with the equipment and limit the operator to the designed limitation range.
- Level 3: Management by delegation; some of crew`s tasks delegated to the automation system, where these tasks are fully automated by a closed-loop controller.
- Level4: Management of consent; the automation system provides regulated multiple control loops, where models describing the well to reach the right control loop. The operator feeds the automation system with the chosen operation, operation goals, and desired values for desired variables.
- Level 5: Management by exception; this mode automation system decides the next operational mode by additional logic, and the operator roll is to monitor and interfere if the system not behave as expected.
- Level 6: Autonomous operation; fully automated system, and the roll of the operator is just to monitor the system.

In all seven modes, the operator still have the authority on the operation and the main decision maker for the whole operation to avoid any risk issues may happen during the operation. These modes have many terms that need to be more explained such envelope protection, closing the loop, multilevel control structures; feedback control, supervisory control, optimization, and autonomy.

2.1.6 Envelope protection automation (Øyvind Breyholtz, 2011)

An envelope protection system take the well conditions in consideration when calculating the boundaries successfully implemented at an offshore installation (Iversen et al. 2009). Therefore, the envelope protection may take the following issues in consideration:

- Envelope protection has boundaries/ limitations depending on the well conditions /information.
- The protection system will just interfere when the driller/operator will exceeds these boundaries.
- Envelope boundaries must calculated dynamically and update the envelope boundaries according to the new well conditions.
- The dynamically calculations required a computational model that is high expensive.
- The envelope protection reduces the frequency of the critical situation when it arises, but not, entirely eliminate them.

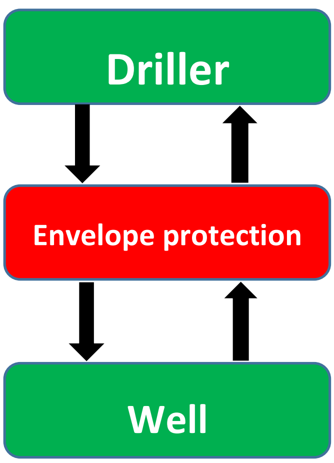


Figure 2. 2: Envelope protection automation (Øyvind Breyholtz, 2011)

2.1.7 Closed loop automation

Closed loop control is higher level of automation than envelope protection system. In this control system, the set point/control value defined and set by the operator either manually or automatically. Automatically; it`s works by using an automated system to find and update the set point. The closed-loop control system using an algorithm to calculate the deviation in the measurement from the desire set point to active an order or process to return the operation to the set point. This type of control system required a large amount of data for the multilevel control structure and decision-making for the whole operation, which can be founded from a data acquisition system. Fig (2.2) shows such a system

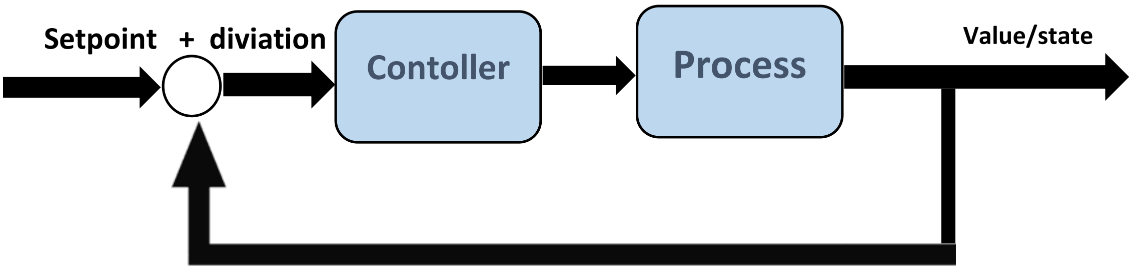


Figure 2.2: Closed loop controller (Øyvind Breyholtz, 2011)

2.1.8 Multilevel control structure (Øyvind Breyholtz, 2011)

The time scale is the key element of dividing the structure of a multilevel control system. Time scale ranges from zero for the upper level and infinity for the lower level because of the difference in the time scale between levels. The higher level coordinate the lower level to reach the goal of the control system. Optimization and decision making depends on the time scale/ time length also, that defining the control level type (higher or lower), which leads all together to decide the suitable systematic control hierarchy needed for an operation such as drilling operation that didn`t used yet. There are three proposed level for a drilling automation system, which are:

- Feedback control level
- Supervisory control level
- Optimization control level

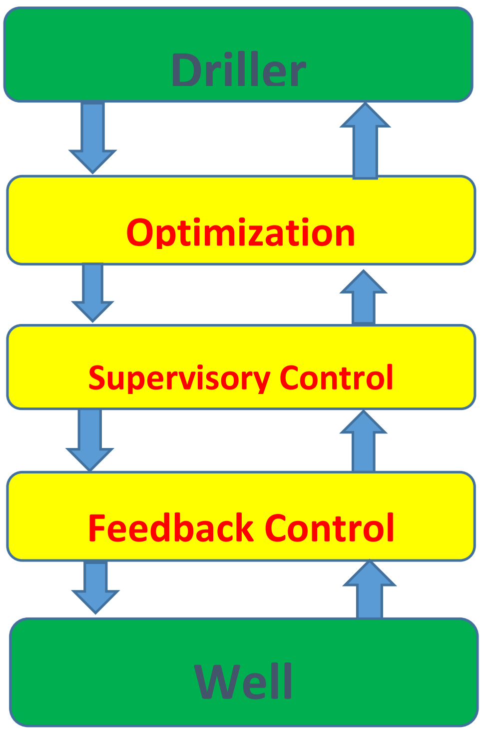


Figure 2.3: Multi-level structure (Øyvind Breyholtz, 2011)

Feedback control

Feedback control used to keep the controlled values equal to the set point. There are many controllers used in industry as feedback controller, but not all of them are suitable for oil industry. The well-known controller used in oil industry is the proportional integral derivative controller (PID). PID controller called also signal-input/signal-output controller, because of using one input to control one output in this controller. PID required high tuning quality to reserve the system performance because poor tuning will leads to that the controlled variables could not follow the set point values. It is recommended to use another controllers if the drilling dynamics is nonlinear, which increases the complicity of the system, and if using of PID controllers is uneconomic because of the high cost of the development, maintenance, and tuning of PID system.

Supervisory control

This level of control can regulate all the low-level feedback controllers by determine the set point for them. Supervisory control can reform the failed controllers with a condition to not exceed the designed cost for the improvement, maintenance, and tuning of the controllers. There are many strategies used in this type of control, but the most useful one is the model predictive control (MPC) because of the ability of handle many variable control issues such as actuator boundaries and operator restrictions. MPC using a finite-horizon open loop to solve control problems depending on the instance state of the well/operation. MPC models can be obtained mathematically or experimentally and the models can be linear or non-linear with a notice that the nonlinear model is more complicated and complex.

Optimization

This level of automation used to improve the whole drilling operation`s performance by find the effective operational condition of the well. That reason make it not essential in high-automated modes and just used to optimize the control system/mode. There is a direct relationship between this level of automation and supervisory control level. The optimization output used as input to the supervisory level, where it includes the optimal values that need to be defined and calculated related to economic and operational conditions. Some of these variables is constant such as time varying disturbances, and others variables such as degree of freedom of optimization. To get the optimum optimization model/level, the variables related have to be defined, solved and the solving result have to be perfect. This will lead to constant set points to reach the almost optimal operation and reduce losses to the designed range. When keeping the operation in the designed range/window, the cost will be reduced, because it will reduce the models needed to optimize the operation, and can reliance a steady-state model that depends upon the low-level feedback controllers and its ability to measure and regulate all the operation disturbances.

Autonomy

This level is the highest level of automation, where the operator role is to decide the level of automation used for the drilling operation, but not interfere the operation itself. The automation system will be able to make the suitable decisions itself and have the ability to change the conditions according to the current well status.

2.2 Drilling automation

Drilling automation is the drilling using the automation applications partially or fully. The reasons of using automation in drilling are as following:

- Increasing productivity
- Lower cost
- Reducing process lead time
- Mitigate human error
- Increase efficiency
- Increase safety

Drilling automation is a desired technology today and expected to be more applicable in the soon future.

2.2.1 History of drilling automation (John Thorgood, 2010)

Automated drilling operations began with the rock penetration when the drill feed used a screw mechanism. Early in the 1860`s, the first automation construction was built for a drilling system to feed a bit with a weight on the bit WOB if the drilling string weight is not enough. This system used a steam driven pump to provide the needed weight on the bit WOB.

No real development in automation happened until the beginning of the twentieth century in relation to the weight on bit indicators but these were either unsuccessful or not practical.

A torque based automation system built at 1920`s, by Halliburton and Hilde, used a torque as a limit to retrieve the casing string if it be exceeded. In the 1930`s a hydraulic feed rotary table was developed and used as an automatic system that limited the propagation because it was slow and not economical.

In early 1971 automation operations started to use computers to control the system by using a digital/analog system to measure the change of the weight on the bit and rotary speed. In 1935`s, a rotary automatic driller system was developed to regulate the weight on the bit by an electro-mechanical device. Five years later, a pneumatic actuated feed control system designed to develop band brakes for the rig.

In 1997, an electronic pit feed system was developed and still works today and this development is used for controlling another operations such as tripping and reaming, drag and torque measurements, pump on/off, and so on.

Automation of the rotary system ran parallel in its development stages where it started as a power swivel and then developed to a hydraulic power swivel and hoist. This system developed in 1970 to an electric power swivel which is used today in a great number of situations as a top drive unit.

The rig floor automation was tightly related to safety reinforcement and this required all the new offshore drilling vessels to be fitted with automated pipe-handling systems. This is still the case today. .

This first began in 1945 when a trial was conducted to make the slips easy to handle by a power slip using a pneumatically controlled slip. A racking system is another form of automation for rig floors and when development it required for the iron roughneck developed by Varco in 1975 to handle the drilling tools on the rig. Racking systems controlled hydraulically through a joystick before using computer controllers that made the system more effective. Then the system was a completely automated controlled system with no human intervention.

Automation of an entire rig had been envisaged with plans and drawings in 1940, but the rig was never built because of the complexity of the design. A semi-automated drilling rig designed for Atomic purposes to drill shallow holes and crewed with two men to control was designed for remotely usage. In 1970, another automated remotely controlled rig was designed for use (42 foot from the floor), but it could not be completely automated because of the need to use people on-site for maintenance activities in addition to that it had no ability to detect and handle the kicks situations. (What is a 'kick' situation – needs to be explained in a short sentence)

There are another automation drilling devices such as a mud mixing system that monitors the mud weight and regulates it according to the drilling conditions. Cementing operations controlled by automation with the use of a recirculating system, which compares the mixed cement to a guide cement value to get an accurate cement density to be pumped down. The bottom hole assembly is a semi-automated depending on the real data availability from BY MWD, LWD and PWD (what do these stand for?) systems to expand the ability of the direct control of the reservoir area.

2.2.2 Why drilling automation (Bromell, 1967)

Safety is one of the most important reasons to develop automation in the drilling industry. Cost is another reason to use automation where reducing the number of human laborers reduces a large percentage of cost issues. . Environment plays a large role in establishing automated systems to avoid many issues such us safety, control accuracy, cost relating to NPT and so on. Automation has a high impact on the efficiency of drilling operations.

Why is automation drilling useful in the oil and gas industry?

Today, automation-drilling costs are law compared with automation in the other industries, but it is increasing with time because of the demand of a system that can reduce the physical and mental workload on human operators and increase economical and operational performance in a way that ensures operational safety as much as possible. Using automation drilling requires a high standard in automation system design to ensure that it does not lead to critical situations and be worse than not using an automation system.

Automation drilling is set up in designing and modeling in many modes to cover the different factors effecting the drilling operation.

2.2.3 Advantages of drilling automation

The automation led and will lead to improve many aspects in the drilling operations as the following:

- Safety
- Reduce labor
- Drilling in a hard weather conditions.
- ROP
- Efficiency
- Accuracy
- Less Rig size
- Rig mobilizing
- Remote Operations.
- Cost

Chapter 3

Drilling automation tools

3.1 Introduction

Drilling automation tools are generally, similar to industrial automation tools in the main title, but not in details. The details related to the automation purpose specifications. For instance, automation system for an airplane using the circumstances and the conditions surrounding any flight from the beginning to the end to build up an automation system. These conditions and circumstances are different for drilling operation rather than the differences for each operation either in airplane automation system or drilling automation system.

Automation tools needs for any drilling operation related to the drilling tools used in a drilling operation, the static and dynamic well conditions that realy exist or occurs during the operation.

Drilling automation systems depends on many functional skills such us: (SPE/IADC 163422):

- Well engineering.
- Process automation control and optimization.
- Instrumentation.
- Modeling.
- Information technology (IT), including software and infrastructure.
- Process control.

The drilling automation tools are different from drilling operation to another according to the functional skills mentioned above, but it can include the following tools:

- Control systems (Model, actuator, and so on)
- Human machine interface (HMI).
- Programmable logical control (PLC).
- Data acquisition systems (DAS).
- Sensors.

3.2 Drilling Tools

3.2.1 Control Systems (Wikibooks.org, March 12, 2013)

In any new idea, some questions coming in mind around this idea. The idea of control system arise two important questions. First, what is the objective of control system? Second, what is the system implementation? When we find the right answers to these questions, this will be the aid element to build up a practical, reliable and robust control system.

The first question related to the activity or the event that we want to make it controlled, and the second question related to the information the control system needs to make the job. While we answering these questions, thinking leads to the details related to the answer. The components forms this system, the structure of the control system, limits, behavior of the system during the activity, and many thing else coming ahead as details.

Control systems or control engineering is a device or many devices connected to each other to control an operation, event, process, activity or physical action. It is also may could controls multi-operations, events, processes, activities or physical actions. Any control system, in general consist of three essential elements as figure (3.1) shows, which are:

- controller
- System
- Measurements

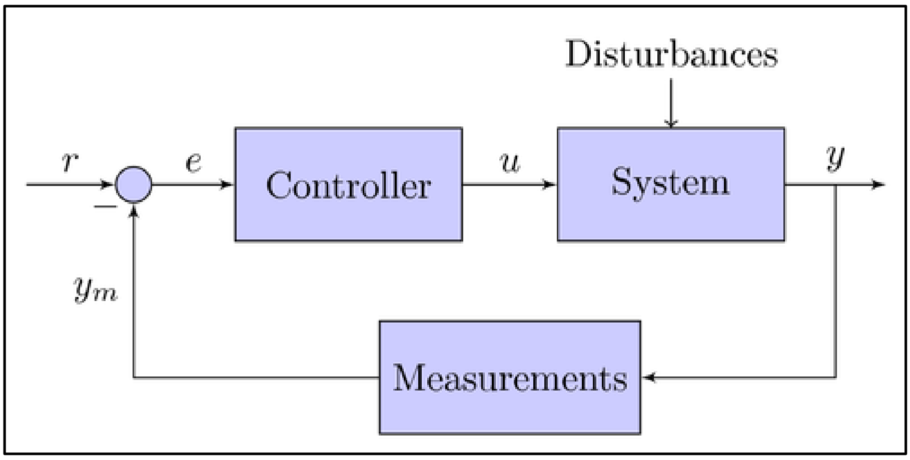


Figure 3. 2: The control system main elements (Wikibooks.org, March 12, 2013)

3.2.1 Branches of control systems

- Classical control; build on the ordinary differential equations ODEs theory.
- Modern control; build on breaking up the high-order differential equation to a system of low-order equations
- Robust control; the outside noise/disturbance formalize the internal error.
- Optimal control; a cost function used to ensure a low cost of the operational system.
- Adaptive control; optimizing the system depending on control response change.
- Nonlinear control; very modern control system used for the process that cannot follow the linear control theory.
- Game theory; a mix of robust control and optimal control.

3.2.2 Classical control system

This system depends on the mathematical approach that builds up the control model by using Laplace Transform and Fourier Transform as a mathematical domain. The main idea used to build up such a system is the high-order differential equations simplified, to let it be able to be used/solved by human, to ordinary differential equation (ODE) by using the Laplace and Fourier transform domain. The classical control covered many topics that were the base of the later control systems.

3.2.3 Modern control system

This type of control system changes the high differential equation to low-order equations following the time domain, not frequency domain, to provide the ability to manipulate these equations, which called state equations, by using the linear algebra. This kind of control trying to provide the ability of immerging the classic and modern control by using computers depending on the division of analog methods from digital methods.

3.2.4 The control system design process (R.5)

The control system design following a specific process could summarized as following:

- Establish the control objective.
- Identify control system model.
- Write the specifications for the variables.
- Establish the system configuration and define the actuator.
- Develop the model of the process, the actuator, the sensor.
- Develop a controller and select key parameters to be adjusted.
- Optimize the parameters and analyze the performance.
- If the performance does not meet the specifications, then iterate the configuration and the actuator, go to step (4).
- If the performance meets the specifications, then finalize the design.

3.2.5 Mathematical models associated with the control system

The mathematical models is the heart of control systems design and optimization. The dynamics changes accompany any physical process needs to be analyzed mathematically to understand and govern such process. Every physical system associated with one or more specific/typical mathematical model depending on the behavior, response, sensitivity, error and other phenomena of the system. Therefore, many mathematical models used for different physical systems such as:

- Differential equations that describes the dynamic behavior of physical systems.
- Linear approximation by using the Tylor series to approach the linearity approximation for the non-linear equations in many different physical systems.
- Block diagram models that represents the variables of the system such input, output, sensor or/and controller. All these variables simplified of the high-order differential equations to subsystems of low-order differential equations solved by Laplace transformer and generated to a subsystem by a transform function. Block diagram reduction used to reduce the number of the block diagrams used for a control system
- Signal-flow graph models used in case of the block diagram reduction cannot/ difficult to representing the control system any more. Using of signal-flow graph model representing clearly the relationship between the system variables and providing a formula for this relationship without the needs of reduction block diagram. The fig. () shows different types of signal-flow graph method.

3.2.6 Programming languages requirement for control system

There are many languages used for control system for programming. The two programs used widely in control engineering as an integrate program for the system are MATLAB & SIMULINX. One of the most known codes used in MATLAB is “sym”, which is a symbolic toolbox used for the Laplace and Fourier transform functions. In addition to that, MATLAB used to write and execute the control/system program with all the mathematical and graphical forms. There are another programs used in the control system design like Matrixx, Simnon, and Program CC.

3.2.7 Types of control

Types of control according to the control method used in the system divided into the following:

- Open loop control; where it has input and output with no feedback and it static system when the operation ends with getting the result.
- Closed loop control; where the input and the output changes dynamically that measured by feedback, which makes the system changes according to that feedback.
- Feedback control; where the action associated with the error occurrence.
- Feedforward control; the system fed with the associated value of control according to the system needs before the error occurrence.
- Linear control; where the output is proportional to the input, which gives a linear result.
- Nonlinear control; where the output nonlinearly proportional to the input, which the output result is nonlinear.
- Proportional, integral, derivative control, where it used individually like proportional control system, integral control system, or derivative control system. On the other hand, it could be combined like PI control system or PID control system.

3.2.8 Controller (Willis, 1998-1999)

Controller is an essential element in the automated MPD to regulate the process and the desired parameter relating to the process such pressure, temperature, mud weight, etc…

There many types of controllers depending on the process requirements and if the process is dynamic or static such as:

3.2.8.1 Proportional - Integral – Derivative (PID) controller

The control system we will chose to look to as a classical control system that still used today with some developments as one of the modern control system components because of its simplicity, effectivity, and suitability to use according to the mathematical and manufacture approach. The name refers to the use of this controller as a proportional, integral and derivative controller. The controller has PID algorithm with three different modes refers to P, I and D modes. These modes either used individually or combined depending on the need of the process to the controller type. There are three terms of the PID controller, which are K_p, K_I, & K_D that represents the proportional gain, the integral gain and the derivative gain respectively. Fig (3.2) shows the PID controller as a block diagram where R is the reference value, e is the error value, u is the input value and Y is the output value.

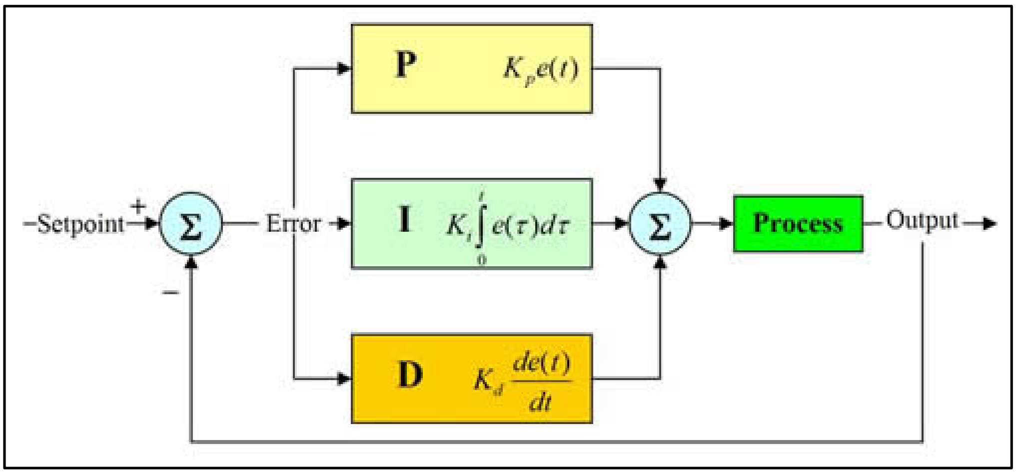


Figure 3.2: The block diagram of PID controller. (Sundar, u.d.)

The control system works as a signal send to the plant to get the calculated output and a sensor will find out the error according to the output value. The PID controller will continuously compute the gain of the controller to adjust the process according to the following formula:

$$u = K_P e + K_I \int e\, dt + K_D \frac{de}{dt}$$

Where:

u: The signal

e: Error

$\frac{de}{dt}$: The change of error over time

Proportional control

There are two types of proportional control

- Open loop control
- Closed loop control

The open loop control consist of controller and system to control the variables desired output (D), input (U), and output (Y), as the fig. (3.3) shows The controller that will control the value of the input U to the system depending on the gain value K and the desired output value D to regulate the output value Y, according to the following formula:

$$U = K.D$$

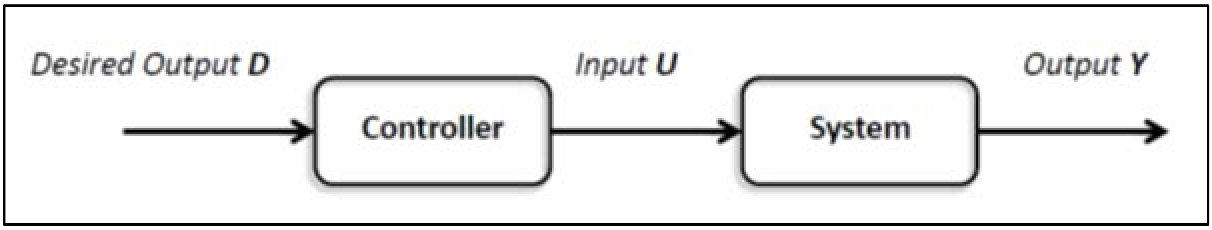


Figure3.3: open loop control (Dr. Matt Stables, 2010)

The closed loop control consist of the components controller, system and sensor to control the variables D, U and Y as the fig. (3.4) shows the variables determined according to the following formula:

$$U = K.(D - Y)$$

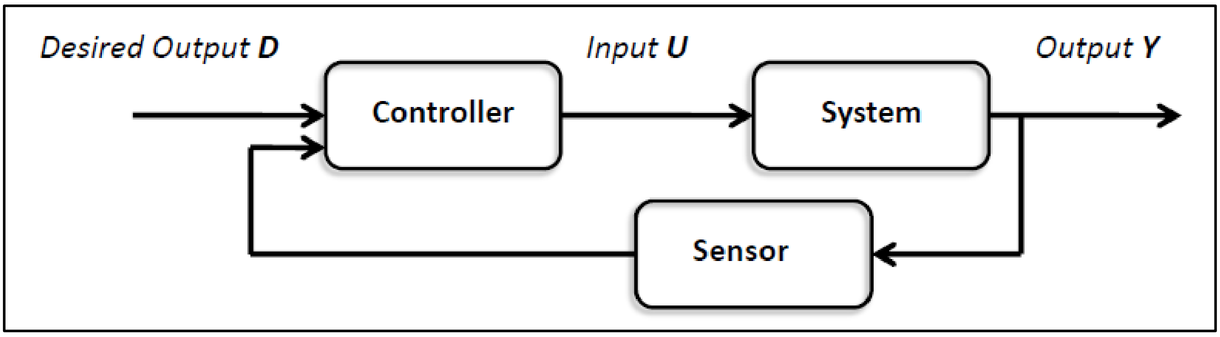


Figure3.4: Closed loop Control (Dr. Matt Stables, 2010)

This formula indicates the proportional to the error in the system; where the sensor measured the output and the controller adjust the input variable according to the difference between the output and the desired input to transfer the result to the system to correlate the output associated to the dynamic changes in the system. Stability of the system determined depending on the transfer function of the proportional closed loop.

The proportional algorithm mathematically refers to time domain.

$mv(t) = mv_{ss} + k_c e(t)$ (Time domain)

In the time domain algorithm, the controller ensure a steady state calibration by the constant term (mv_{ss}). In all situations, the proportional algorithm reduces error but could not eliminate it.

Proportional Integral control

This controller has the ability to ensure a zero steady state error by correcting the error value, between the set point and the output value automatically during time, by adding the integral mode that represented mathematically as:

$$\frac{mv(s)}{e(s)} = K_c\left[1 + \frac{1}{T_i s}\right] \quad \text{or} \quad mv(t) = mv_{ss} + K_c\left[e(t) + \frac{1}{T_i}\int e(t)dt\right]$$

This type control disadvantage is that reducing stability and increases the system complexity.

Proportional, integral and derivative controller

This controller comprise of the three types of gain K_p , K_I, & K_D where the controller tries continuously reach the needed output response. The following mathematical relationship represents the PID controller algorithm:

$$\frac{mv(s)}{e(s)} = K_c\left[1 + \frac{1}{T_I S} + T_D S\right] \quad Or \quad mv(t) = mv_{ss} + K_c\left[e(t) + \frac{1}{T_I}\int e(t)dt + T_D\frac{de(t)}{dt}\right]$$ (Willis, 1998-1999)

Depending on the derivative part in the formula T_D that representing the rate time, the dynamic response of the system should be improved. Noise signals effect negatively on the performance of the controller by effecting the derivative part.

Types of PID controller (Pearson Education, 2002)

There are different types of PID controllers according to the type of algorithm they use. The difference in the algorithm provides different act for the PID controller on the error or on the measurement.

- Ideal PID; where the algorithm acts on the measurement
- Series PID; the algorithm acts either on the error or on the controller.
- Parallel PID, the algorithm acts on error.

This different kind of algorithm and the PID as well effecting on the types of tuning and regulating methods used for the PID controller to improve the performance of the system and the PID controller as well at the main performance characteristics, which are:

- Overshooting
- Rise time
- Decay ratio
- Settling time

It will not discussed further details of these characteristics by now and the reader can get more details, if needed, from references.

It is considerable to notice that the performance characteristics used as a design factors in the process of PID design, where every factor of the mentioned above should be improved by adding a specific control to the controller design. For instance, rise time improved by adding proportional control, overshooting improved by adding a derivative control and adding or adjusting other controls will improve the whole process.

Controller Algorithm (Sanders, 2009) (Anon., u.d.)

The name came from the famous Muslim scientist AL Khwarizmi born in 778 that put the base of algorithm science. Algorithm is an infinity time and space steps to be performed used in many processes where automation is one of them.

Algorithm can be classified in many different ways based on implementation, design, optimization problems, by field of study, and by complexity. The automated MPD depending on the design methodology or paradigm method to build up an algorithm and sometimes mixed of two or more of the classified methods. Divide and conquer algorithm is one of the method used in automated MPD that based on reducing the problems instance to make it easy and effective to solve the problem. Another type of algorithm used in automated MPD is reduction of complexity algorithm that reduces the complexity of the problem to get the robustness and simple solution for the problem.

Segmentation algorithm used in the event predicting method to handle the event occur at the right time that provide a stable drilling operation along drilling time which increases productivity and reduce non-productive time NPT.

Control algorithms implementation and optimization is more than common in automated MPD in the different MPD methods and especially for the dynamic processes. This control algorithm based on the process variables, the repetition of the process vocabulary, and the predicting of the events occur during the process.

Algorithms used in different types of simulation for different applications of drilling operation to analyze, optimize and develop the operations performance.

Controller Tuning (www.home.hit.no, u.d.) (SPE, 2005)

Tuning is a process used to determine the parameters of the controller (K_p, K_i and K_d) to be used to reduce the error between the measured value and the desired set point value of the controller. Tuning the controller variables and parameters will optimize the operation process.

There are many tuning methods depends on the type of the controller used, but generally, there are two main tuning methods, which are:

- trial and error method
    - flow
    - level
    - pressure
    - temperature
- process reaction curve methods
    - Ziegler-Nichols method
        - Closed loop method
        - Open loop method
    - Cohen-coon method
- Internal model control
- Auto tune variation

If the process have no mathematical controller, the method would use an experimental way to find the controller parameters such as Ziegler-Nichols method. While the other type called model based method that depending on the mathematical function of the controller to determine the controller parameters.

Tuning for a dynamic drilling process required continuously updated data measurements such as hydraulic fluid model and the parameters related to it like pressure, temperature, rheology, density and so on. Real time measurements for these parameters with a suitable estimating technique using filtration would be a good basement for successful tuning to obtain high degree of accuracy.

3.2.8.2 Model Based Controller (P. E. Orukpe, 2005) (www.seas.upenn.edu, 2008)

Model based controller used MPD application named underbalanced drilling (UBD) that can handle control of multi-phase flow that required many models to predict the flow parameters and pressure change in the well additional to many simulations to cover the continuous change in the flow regime and pressure values. The controller design concept depends on simplify the model to make it easy to use and robust to avoid uncertainty that may deviate the model output value from the desired set point value.

Model based controller means that the model design based on one parameter or more in the drilling operation. For instance, model based BHP controller that depends on the BHP as a set point and all the other parameter manipulated according to this set point value.

The model-based controller may use more than one parameter as a based parameter, but according to the model design and performance experience, this may leads to model uncertainty and increase the model complexity. As illustrate above, model simplicity is one of the model requirements to ensure high control performance.

The model based controller using some advance controlling methods or regulators such as linear-quadratic-Gaussian regulator (LQG) to improve the controller performance that is not the field of the thesis research to go deeply in the details. But, this method and many other methods used in controller design in automation that may require more focus for other types of engineers than automation engineers to be familiar with automation design associated with well design.

3.2.8.3 Model Predictive Controller MPC

This kind of controllers used for advanced dynamic process to predict the dynamic change occur in the operation. The theory behind this model is iteration and finite horizon optimization of a system.

The main feature of this model is to predict the change and behavior of the variables relating to the process and handle these behaviors by an algorithm called a numerical minimization algorithm. This algorithm based on the internal dynamic model of the process and repeating this process over time depending on the new process data to optimize the predicting model over time.

This model is more practical than PID and LQR controllers because of the dynamic ability it has to predict the process variables. This type controller is common for chemical processes, but it could be practical for the dynamic MPD application such as under balanced drilling (UBD).

3.3 Real Time modeling and monitoring

Many automated MPD applications depending on real time measurement to detect and manipulate drilling problems such as kick, losing circulation and so on. Real time data and data measurements is essential in the new modeling automated control systems used in drilling and specially in MPD operations.

Real time modeling means models that depends real time data in its design and performance. Real time data required specific equipment and tool to obtain measured or monitored data for the drilling parameters related to each model. Today, there are some sophisticated real-time service applications

Additional to real time data measurements that used for model design and tuning, real time data monitoring also important to detect drilling problems earlier and take an action to solve them. There are many equipment and application used to obtain real time date for monitoring and modeling purposes in drilling industry used today to improve the drilling operations.

3.4 Human machine interface HMI (Zhang Yinghui, 2011)

As a definition, there are many definitions for HMI, but all of definitions meet each other in a general meaning, which means that Human machine interface (HMI) is a link, mediator or the relationship between human and machine. Earlier, HMI called MMI, which means Man Machine Interface that later changed to HMI to generalize the meaning to include both men and women as a labor community. HMI could be a software or hardware make that kind of interface between human and machine. HMI can be defined also as user machine communication by using various communication tools such as PLC (Programmable Logic Controller), PAC (Programmable Automation Controller), and so on. The interface method between the user and machine could be different from an application to another, such as visual and physical. Therefore, HMI can be classified according to the interface methods to visual such as monitoring, physical such as drilling chair in drilling operation or both visual and physical as in the control room that requires monitoring an operation and taking an action according to that. (Anon., u.d.)

There are some examples of HMI in the normal life such as mini banks, benzene stations, medical centers paying automat and many other examples. In oil and gas industry and specially in drilling automation system, the HMI level depends on the level of automation explained in chapter 2. At the full automated level HMI will confined to monitoring the drilling operation, while HMI roll will increase with the decrease of the automation level because of the increase of the human interface with machine for both monitoring and decision making.

The HMI must designed to match the drilling automation requirements and ensure mitigating human error. Some studies conducted to develop HMI design, which depends on three categories, process/system analysis, risk management, and human error.

It is necessary to consider some factors when design and implement a HMI system, such as:

- Time delay between HMI and PC.
- Error of data transformation from analog data to digital data.
- Safety communications between PC and HMI.
- Security strategy for HMI formula data.
- Structure of database.
  - Storage space of database.
  - Data access mode.
- HMI formula creating.
  - Calling formula.
  - Editing formula
  - Transferring formula.

3.4.1 Delay time effect on HMI and automation system

Time is one of the main issues take in concern to build up an automation system and a HMI design as well. The system efficiency recognized by the time delay between the system elements. High time delay refers to low system efficiency, and low time delay represents a high efficiency level of the system.

The time required transferring data from/to PC to HMI could be calculated and there is a designed limit for this time if it were exceeded, the system will be recognized as it have a delay time. Delay time depends on the communication module network used, the communication function, protocols, and many other factors could affect time to cause a time delay.

3.4.2 Safety communication between PC and HMI

The safety communication between PC and HMI depending on the communication module conducted between them. Communication module have different types such as cable, internet, pulses, signals, and so on. All these types depends on the transferred data formula used in the system, and type of privacy it has to ensure a safe communication to HMI.

For instance, in internet communication method, there are protocols that data transferred through it, and every protocol has a level of safety depending on the sensitivity of the purpose it used for it. The communication module, as usual, has a protecting encrypt keys and codes to arise the safety level such as firewalls in the internet communication module.

HMI has a direct and indirect connection to the other components in the automation system, such us PC, PLC, SCADA (supervisory control and data acquisition), SAS (Substation Automation System), RTU (Remote Terminal Unit) and many other components may implemented in various automation systems. The connection defined according to the effect of the function on each other. For instance, us it mentioned above, the relationship between HMI and PC depends on the quality of both of them that leads to the quality of the system.

3.4.3 Security Strategy for HMI formula data

The security strategy conducted to build up a HMI design playing an important role in the quality and security of the design that ensure minimum human error and best execution quality in any automation system, especially for the sensitive ones that may result to high economical, operational and human risk. Therefore, it is important to consider the safety way of using data transferred between human and machine and recognize which data will be available to use by human and how.

The HMI design conduct specific process to ensure security such as the way of data download, the amount of data available for the user/operator, the responsibility of modify data when needed, and the cods and encryption used through every stage of design and implement of HMI.

3.4.4 Structure of database

Database structure is a main and important issue to design a robust and practical HMI design. This issue depending on the purpose of HMI design to consider the storage space needed for the design, and the access mode conducted for this design.

3.4.4.1 Storage space of the database

The storage space needed for HMI design depending on the parameters treated in this design. Usually, storage space is a kind of memory needed that calculated by indicate the parameters and the storage needed for each one. The storage space in byte, therefore the total parameters storage space will be in thousands of bytes.

3.4.4.2 Data access mode

Data access means how to reach the data stored in HMI system. Data access has two types, reading data access (R/O), writing data access(W/O), and reading and writing access (R/W). HMI have to be connected to PLC to ensure an access, but it called also offline access if it not connected. The access method is different from mode to mode of HMI. Some modes using serial connection such as Ethernet to connect to PLC, which named TELLUS HMI mode that gives the possibility to connect HMI to PLC by using windows software. Another mode named VDS software mode using HMI server function and HMI client function as a method of data access. The known mode used in drilling named SCADA-HMI mode that using a web and wireless access to SCADA with internet/internet support. This mode enables a remote wireless access from any PC to get a real-time data access.

3.4.5 HMI formula creating

Every HMI design needs to create a formula associated with the number of parameter the system has. These parameters represent the system main and sub-processes that may increase or decrease with time associated with the change of the processes of an operation. Some automated system has constant number of parameters lead to create an unchanged HMI formula by time that is unrequired for such systems. These systems may called static automatic systems. While the other systems, which called dynamic automation systems that has a dynamic change in its processes and conditions, needs to establish HMI formula that have the ability to change or accept additional parameters. This formula type used for a dynamic automation system that provide an ability to add new parameters by this formula.

The established formula quality measured by three elements, calling formula, editing formula, and transferring formula. When these three formula elements level is high, the formula quality is high, or vice versa.

3.4.5.1 Calling formula

As quality is relating to two important thing associated with the formula establishing, which are time needs to call a parameters of a formula, and the ability of insert a new parameter in the formula and the time needed to do it. Time that is an important issue in the whole automation system is the central issue to recognize the performance of a formula.

3.4.5.2 Editing formula

It is possible to edit any formula by calling the formula number, make the necessary modifications, and save it at the same formula number. This process provide the ability to follow up the changes in every parameter and rewrite it to be associated to the new condition.

3.4.5.3 Transferring formula

Every formula has a number that used to transfer the formula to the HMI interface when the automation system works. The formula transferring conducted through a transferring program. This program calling the specific formula, by formula number, when it be executed to conduct the transferring.

3.5 Programmable Logic Controller PLC (Wikibedia, u.d.)

PLC is a control system used prodominantly in automation in industy generalt and especially for oil and gas industry. PLC consist of three words that explaining the meaning of PLC. The first word “Programable” indicates using of a program that has the ability to change and reprgrammed. “Logic” refers to that the program forllowing a logic programming language. While “Controller” refers to this programmable logic unit is a controller acting as a control system.

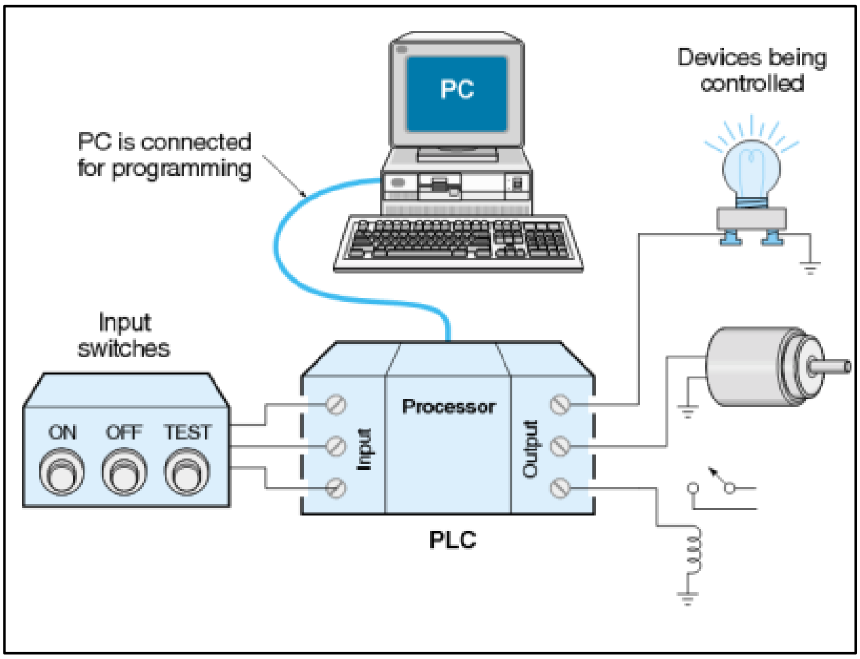


Figure 3.5: PLC components (Anon., u.d.)

PLC, as a difintion, is a computer control system that is a processor control system with high technical level exceeds the normal computer level because PLC manufactured to tolarate hard working conditions like temperature, pressure, moisture, dust and vibration. PLC has many features such as relay control, motion control, process control, distributed control sustem and networking

The feature that is more related to this thesis is process control that required a contiously moitoring a process and control the process event and react to this event.

PLC consist of four main units:

- Input unit
- Central Process Unit CPU
- Output unit
- Communications

3.5.1 History of PLC

First time PLC proposed by Dick Morley, who considered as the father of PLC (Wikibedia, u.d.) at 1969 to replace relays that was not practical especially if there is a need to reprogram it because of the time used to rewire the relay and add more units to handle the process change. Therefore, PLC invented to enhance the functionality of the control system.

PLC developed with time in many stages related to optimize the programming languages used, functionality, and training procedures. The first programming language used for PLC was relay-derived ladder logic and still used today because of simplicity to use by user or programmer. Many other programming languages used also with time such us BASIC, C, C++ and others, but ladder logic still the preferable one because of simplicity as mentioned.

3.5.2 PLC units (AMCI, u.d.) (PLCS.net, u.d.)(Wikibooks, u.d.)

PLC consist four main units, as mentioned above, that represent the general structure of the PLC, which are input unit, Central Process Unit (CPU), output unit, and communications.

The input unit, that called also input scan, is a memory unit contains of all the input data/elements needed for the process and connected to many sensors to update the data input. Number of sensors depends on the process elements that needs to check.

These data used of the next unit, CPU unit, which called also program scan execute the control program that treated the input data according to the limitations and boundaries set by the programmer/user and send the results to the output unit. The CPU connected, as usual to a PC for reprogramming.

The results of the CPU unit send to the output unit that adjusts the devices connected to the output unit according to the values sent from the CPU. The output unit consist of an actuators to adjust the result values come to the output unit from the CPU.

The communication unit provides the connection between the three mentioned units above to each other and to external units/devices such PC, another PLC if needed, and internal diagnostic units. The diagnostic units/devices provide various features to recognize the system faults syndromes and sending messages to solve such problems or at least mitigate them. PLC is a loop operation that repeated to update the process according to the changes happening in the process conditions.

There are many issues needs to consider when design and build up a PLC control system such as:

- Response Time.
- Programing
- Security
- Simulation
- Redundancy

Response time depends on the process complexity and whenever response time is low, the PLC efficiency is high. Response time as usual is millisecond and industry looks always to optimize response time to ensure a high reliable control system.

Programming general in the concept of PLC for all the manufactures, but it is different from language to another in details like language codes (I/O) and the memory saving method, which make the compatibility between the programs difficult. PLC programing languages are many like function block diagram (FBD), ladder diagram (LD), structure text (ST) that is similar to Pascal programing language, instruction list (IL) that is similar to assembly language, and sequential function chart (SFC). Security and simulation associated with the consequences of any leak in these issues. Communication unit attacked if there is no associated security level to prevent such attack especially between computers. Simulation provide robust program before activating the program by test the PLC program to avoid the time consuming relating to the down time fully or partially.

3.6 Data Acquisition System (DAS) (Jon Park, 2003) (Anon., u.d.) (Monitor Systems, u.d.)

Data acquisition system defined as a system includes many components that provide converting data from physical type to digital type through several components act as converters, and then convert the digital data, by-data distributing system to different outputs depending in the process type. Data distribution system is not part of data acquisition system, but it is important to close the process loop by converting the digital data to analog data with using of D/A convertor.

A simple DAS consist of the following hardware components:

- **Transducers**, which converts the physical parameter (pressure, force, temperature and so on) to an electrical signal.
- **Amplifiers**, which rise the low-level electric signal (millivolt) to the suitable level needs for the next processing (1-10 Volt).
- **Filters**, which reducing noise and high frequency
- **Nonlinear analog functions**, which adjust the high level signal to the next step by many operations such as dividing, multiplication and so on.
- **Analog multiplexers**, which consists of many input-output channels to switch between them according to the input analog and the output digital. It save the converted data during the converting time and the output results goes to another digital circuit or to a computer data bus.
- **Sample- holds** which in cooperative with the analog multiplexers save and share data with many input channels.

The DAS called the interface between the physical phenomena and the digital computation and control "analog- digital interface". The DAS main feature is to collect data for any physical action to use it for analyzing, documenting, or both. DAS consider as a real time data provider also that used in many industrial discipliner such as Automatic control systems in many industrial aspects where oil industry, the thesis subject, is one of these industries.

Every DAS has an important device that provide the analog -digital interface called A/D converter and for DDS (Data Distributer System) that it's the opposite of DAS, the data converter will called D/A converter, which is acts like digital- analog interface.

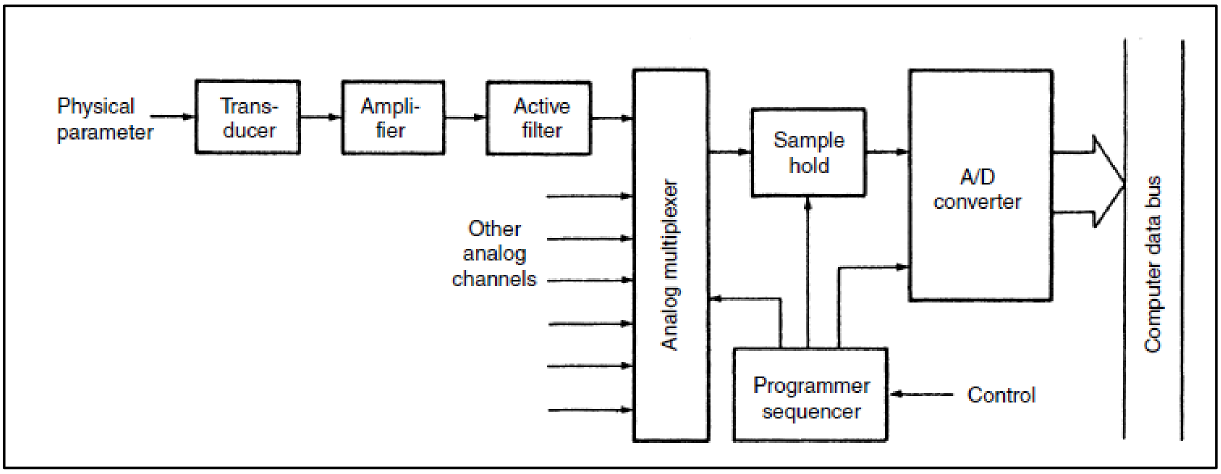


Figure 3.6: DAS Data Acquisition System (Anon., u.d.)

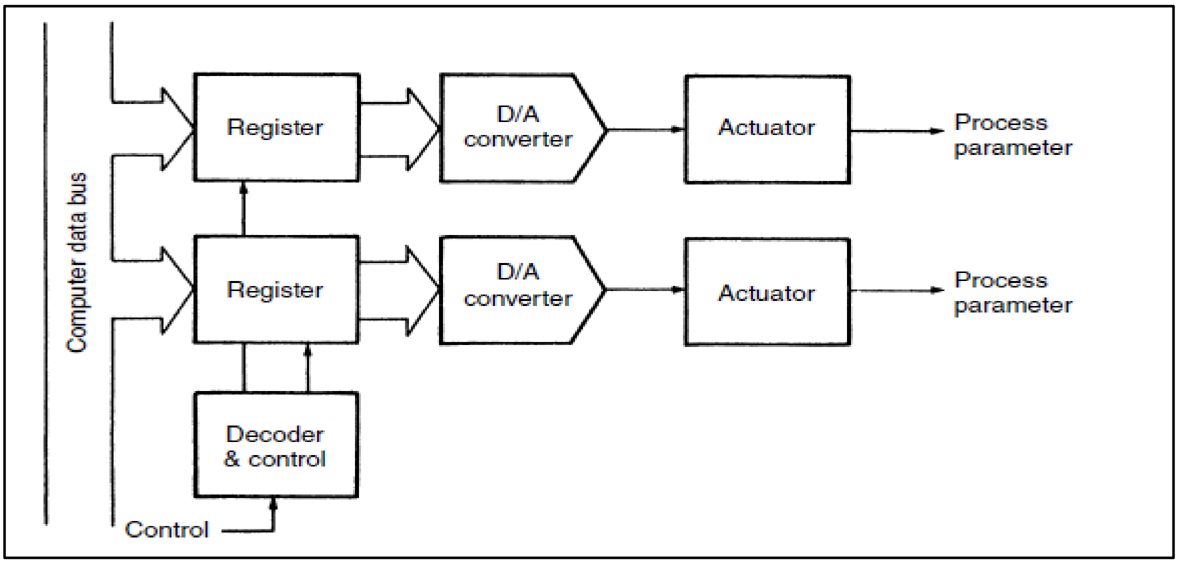


Figure 3.7: Data Distribution system. (Anon., u.d.)

To document data related with a process, the data acquisition systems using different ways to achieve the document process such as recorders, data loggers and hybrid recorders. Recorders using pen and papers in continuously readable output, while the data loggers printing the values with high resolution of reading, less use of paper and better interpreting. The hybrid recorder is a combination of the two types mentioned above.

Computer used in DAS depending on the level of the process and the user skills. Computer classified according to the way of connection to DAS, where some of them using plug-in method of connection and others as standalone and connected to DAS through communication port.

The communication ports varies from the simple one as data logger to the remote intelligent type. Different types provide different communication interface vary in the distance (short or long) and the speed (bits per second) that relating to the number of connecting bits.

DAS card is a plug-in method directly to the computer that provides high speed and low-cost relating to the other methods. In addition, the card has a specific input/output memory access in the computer that provides data safety and data access speed.

DAS implementing software as a modern and effective way to deal with data documenting and converting in term of high and safe performance. Software became important component of the data acquisition system because of its compatibility to all products, even the latest modern industry.

Many applications used DASs to provide data and the ability to analyses data. Monitoring used widely the DASs to accomplish its work depending on real data existing and further processing features.

In automation drilling, information/data management used widely to achieve high safety, effectivity, productivity and low cost. There are many DASs systems used in automation drilling today that depending on the availability of data at real time, data analyzing and data use for further processing. Many drilling activities and equipment required real time data and data management, such as drill equipment information (drill string, BHA, Bit, so on), mud information, geology information, and many other parameters and equipment. All these information/data inputs into the DASs for storage, analyses or send through a data distribution system to be used in a specific process. The data sources input to the DASs divided into three types of data environment data includes surface and subsurface data, human observation, and measurement data. (Thonhauser, 2004)

Data acquisition system has some important concepts connecting to the design and the implementing of the system that:

- **Data quality**, which is especially highly important to the analysis process that depending on the input.
- **Data collecting method** that effecting directly the quality of data collected.
- **Data Storage space** that it reduced continuously by removing the useless data and keeping the data used for a particular processes and applications.

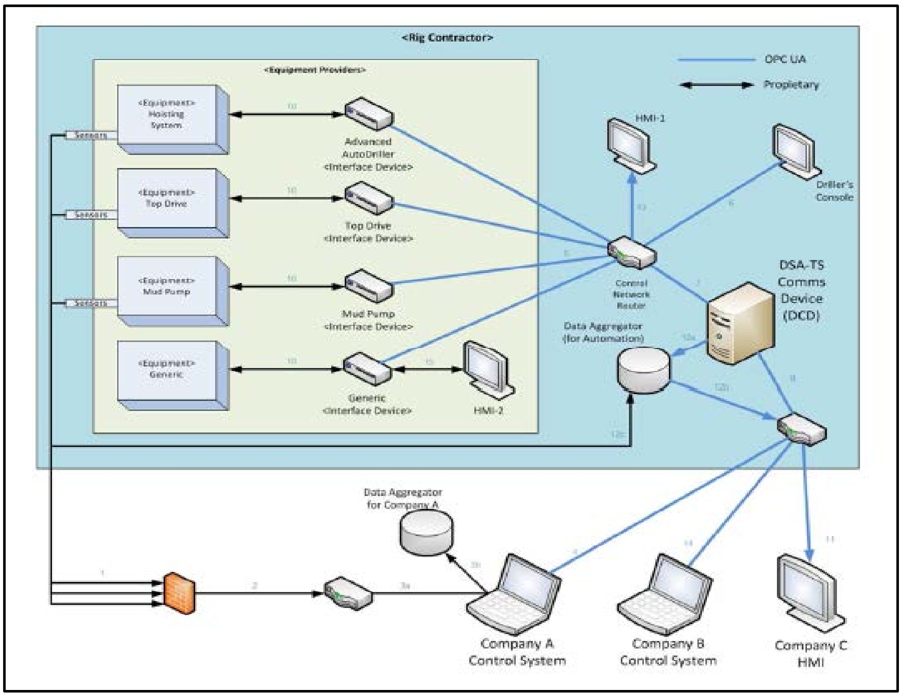


Figure 3.8: DAS- TS automation structure. (Chapman, u.d.)

- **Data safety** through using standard exchanging data language, such as XML and WITSML.

MH Drill View system is DASs, which has the features of acquisition, logging, storage, storage and display of drilling data. (Aker Solution, u.d.)

DSA-TS Comms Team is a control system developed by Schlumberger to build up an architecture of the data and process system with four phases: (Chapman, u.d.)

- Interface points and communication protocol
- Components definition and levels
- Automation drilling process terminology and components interface.
- Commissioning test
-

3.7 Sensors used in control systems (Åström, 2002) (Schuster, u.d.)

Sensors used today almost over all industry as a part of industrial control systems especially in automation drilling as an important component of DAS system rather than many other processes and applications. Therefore, it is important to identify and define sensors, types of sensors, specifications and applications of sensors.

3.7.1 Sensors definition

Sensors have various definitions relating to the fundamental of it, but it generally defined as a device or element that converting a physical phenomenon/input to a suitable output, or producing signals as a measurement of a quantity or physical action. In other word, sensors sensing any kind of input such as physical, chemical, thermal, sound and so on to convert it to a readable signal to a specific output such as DAS, control system, actuator, or any connected device/ element related to the process designed before.

3.7.2 Specifications of sensors

All sensors have general specifications that could match each other, but it is not conditional that they are collected in one sensor, that it could be possible for high-specified sensor. The specifications are as followed:

- **Range of input** that vary from sensor to another depending on the feature of the sensor. For instance, temperature sensor has range of 25-225 °C.
- **Span** : $\text{Span} = \text{Max. input} - \text{Min. input}$
- **Error**: $\text{E} = \text{Actual Measurement} - \text{True Measurement}$
- **Accuracy**: $\text{A} = \mp \text{full range output}$
- **Sensitivity**: ratio of change in output to the change in input. $\text{S} = \frac{\Delta \text{ output}}{\Delta \text{ input}}$
- **Nonlinearity**: the maximum deviation of the actual curve from the linear curve.
- **Hysteresis**: is the error of the sensor at any point of the measurement.
- **Resolution**: $\text{R} = \frac{\text{Max. input}}{\text{Max.output}}$
- **Stability:** constant output for constant input over time.
- **Dead band/time**: range of input values without output.

- **Repeatability**: a same output for same input for a repeated measurement.
- **Response time**: time indicates the speed of the output change.

3.7.3 Types of sensors

The types of sensors related hardly to the applications that the sensors used for, as follows:

- Displacement, position and proximity sensors.
- Velocity and motion sensors
- Force sensors.
- Pressure sensors.
- Flow sensors.
- Level sensors
- Temperature sensors.

Another sensor type's classification divides sensors into two groups engineering sensors, and biological sensors that includes almost all the mentioned above sensors with further additional sensors types as follows:

- Engineering sensors
    - Light intensity
    - Humidity
    - Pressure
    - Temperature
    - pH
    - time
    - distance
- biological sensors
    - light density
    - sound
    - level, rotation
    - chemical composition
    - temperature
    - air flow
    - gas composition

3.7.4 Sensors and control systems relationship

Sensors has a direct effective relationship to the control systems, where sensors has the feature of converting the measurement result coming from a physical phenomenon to the control system. This converted value of the measurement as a signal will indicates as input to the automated/control system to produce an output by the controller to an actuator that act in a way to keep the result output near possible to the desired set point.

As a relationship connecting the sensors to the data acquisition systems (DAS), the physical and electrical phenomena indicated as non-steady state variables. These variables needs to be converted to the data acquisition systems in term of make it readable form for the human. This converting process utilize by the sensors that may called transducer, which enables converting the physical phenomenon to an electrical or electronic signal to the data acquisition system. The data acquisition system has the capability to measure a hundreds of variables at the same time, which has many channels to display the results in many ways such paper charts or readable printed sheets and modernly using the personal computer for this purpose. DAS discussed earlier in the section 3.4 of this chapter.

Chapter 4

Modeling and automation drilling

4.1 introduction

It is important to define the meaning of a model before going through the specification of the model that will be discuses later in this chapter. According to the business dictionary definition, the meaning of a model can be define as:

"Graphical, mathematical (symbolic), physical, or verbal representation or simplified version of a concept, phenomenon, relationship, structure, system, or an aspect of the real world. The objectives of a model include:

- Facilitate understanding by eliminating unnecessary components
- Aid in decision making by simulating 'what if' scenarios
- Explain, control, and predict events based on past observations.

Since most objects and phenomenon are very complicated (have numerous parts) and much too complex (parts have dense interconnections) to be comprehended in their entirety, a model contains only those features that are of primary importance to the model maker's purpose.

Models range from simple sketches to computer programs with millions of lines of codes, but all of them have one thing in common: some elements of the actual 'thing' are abstracted or mapped into the model.

Models divided into three classes based on their degree of abstraction:

- Iconic model: least abstract, physical, 'look-alike' model, such as a model airplane or train.
- Analogous model: more abstract but having some resemblance to what it represents, such as a chart, graph, map, network diagram.
- Symbolic model: most-abstract model with no resemblance but only an approximation to what it represents, such as a mathematical equation or formula, financial statement, language, and set of accounts. See also mental models.

  Read more at: http://www.businessdictionary.com/definition/model.html#ixzz3XqAtuPi1 "

All the models structure almost following the definition of the model described. Generally, the drilling models discussed according to the following procedure:

- Model's role, prediction, controller design, and fault detection.
- Modeling that discussing the mathematical concept of the model
- Model calibration
- Models future work

Figure (4.1) shows the general modeling concept that contains of following aspects:

- Assessment
- Action
- Acquisition
- Analysis

The structure inside the main four aspects shows how these four aspects defined in the actual drilling operation. Where the action defined by the drilling and tripping operations. The acquisition defined by the data from the action part that needs to made some analysis on it to be simulated and modeled. This modeled data transferred to make a decision for the next step to make a new action to close the loop/cycle. The assessment is the repeated and continuous mission that starting by action and ended by action again, or never ended.

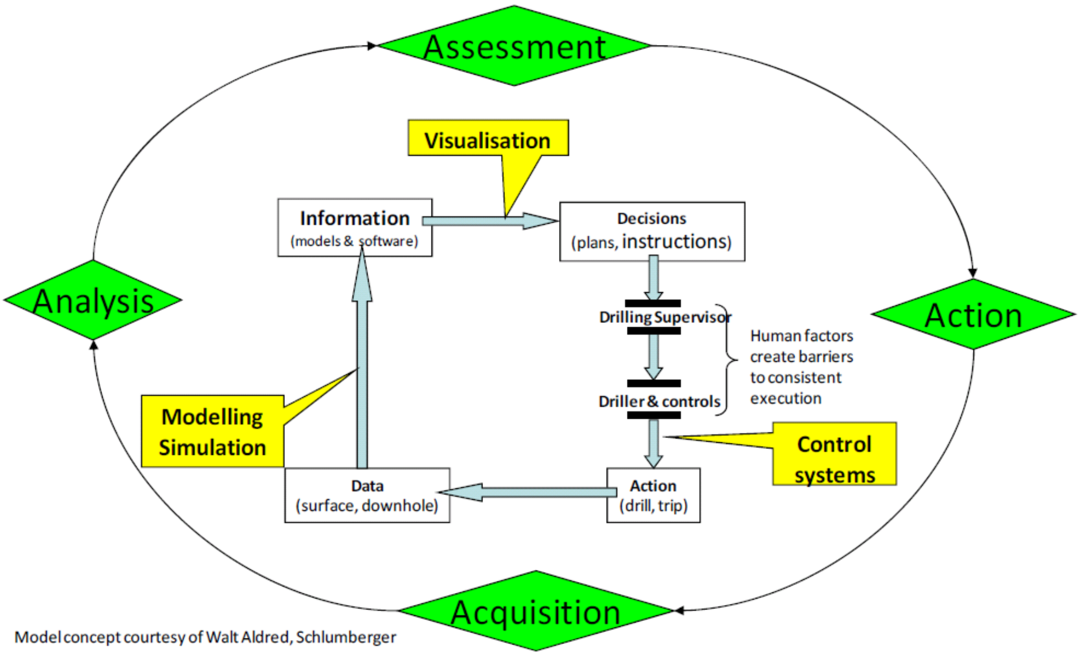


Figure 4.2: Modeling concept (Thorogood, 2012)

4.2 Modeling and models

Drilling operation is an operation that dealing with many physical phenomena in a way that drilling operation effecting these physical phenomena and the reaction of these physical phenomena effecting the drilling operation. These physical phenomena can be summarize to the following:

- Wellbore properties
- Hole section
- Drill string section
- Well path
- Drilling mud section
- Circulation
- Pore & fracture pressure
- Geothermal gradient

These physical phenomena effected by the drilling operation parameters such as rotation speed of the drill string, flow rate, pumping rate and so on. There will be a reaction by the physical phenomena on the drilling operational parameters. This reaction occur because of the operational parameters effect on physical phenomena that may leads to occur drilling problems.

MPD application used today to minimize and eliminate most of these drilling problems by taking in consideration the modeling concept of the physical phenomena effect by and/or on the operational parameters, and try to create a practical model for every phenomenon.

The models that considered in the drilling application are:

- Hydraulic model
- Rheology and density model
- Temperature model
- Torque and drag model
- Hole cleaning efficiency control
- Data acquisition control
- ROP optimizing

4.2.1 Hydraulic model (Mæland, 2013) (Professor A. Dosunmu, 2011) (Boge, 2013) (Glenn-Ole Kaasa, 2011) (Ulf Jakob F. Aarnes, 2011)

Hydraulic model is an essential and important part of the managed pressure drilling control that is concern about all the physical phenomena effecting the pressure during drilling. The main objective, if the drilling control system is to control the pressure in the well, to ensure a safe and effective drilling operation. Drilling operation controls the bottom hole pressure to keep it between the drilling window that will not exciding the fracture pressure and not less than the pore pressure, with help of back pressure compensating the annular pressure instability.

An automated drilling system is a closed flow system using the following elements to control the flow in the well during drilling:

- Rotating Control Device (RCD)
- Choke manifold
- Backpressure pump

RCD responsible of circulating the fluid during static and dynamic drilling to keep the flow continuous and keep the BHP constant to avoid any kind of influx in the well or loose circulation to the formation. The choke manifold controls the flow rate in and out of the well based on the pressure differences in the well by between the surface pressure and the well pressure. In case of influx or loosing circulation that effecting the pressure inside the well positive or negative, the backpressure pump with incorporating with the choke manifold compensate the pressure in the annulus..

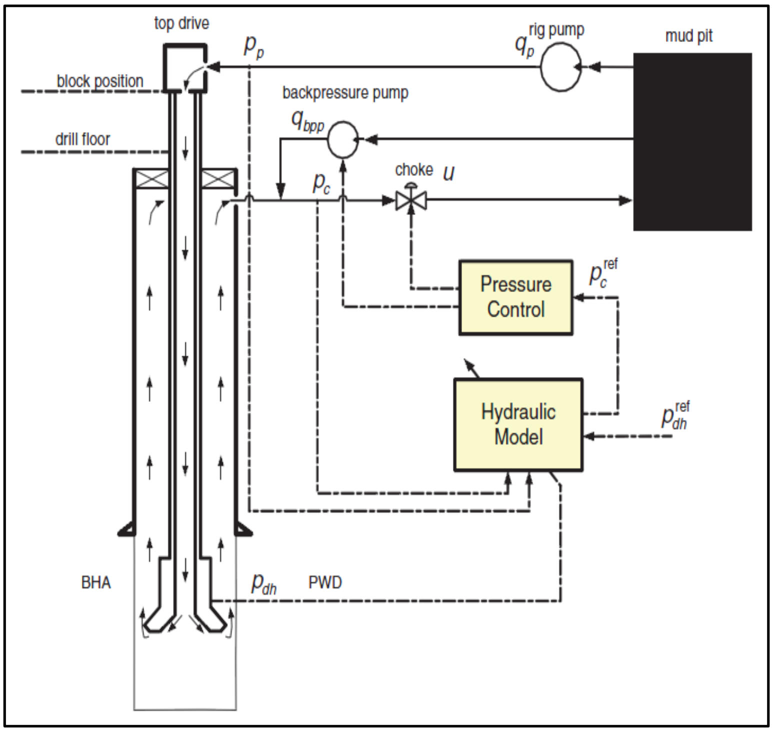


Figure 4.3: The automated MPD system schematic (Mæland, 2013)

Fig (4.2) shows the MPD system schematic, where P_p is the pump pressure, P_{dh} is the downhole pressure, q_{bpp} is the backpressure pump flow rate, q_p is the pump flow rate, P_c is the chock pressure, P_c^{ref} is the reference chock pressure, and P_{dh}^{ref} is the reference downhole pressure.

The hydraulic model require a continuous surface and downhole measurements to update the model data required to the hydraulic mathematical modeling. There are many aspects effecting the mathematical model calculations that may affect the model accuracy.

The hydraulic model according to the data input to the model from surface and downhole measurements predicting the required backpressure, choke opening position, flow rate, ROP, mud density, mud rheology, and sometimes the pore pressure and fracture pressure to keep the well pressure in the drilling window between them.

There are many different designs for the hydraulic model depending on the drilling application, the well specifications, the weather and environment, and other technical and economic issues. Hydraulic model design and the controller design based on some constants and variables that forms the general shape of the design, then during design development may add some changes to the main design to make it suitable to the development changes. Today, the oil industry trying to adopt a universal dynamic hydraulic model has the ability to follow the well parameters changes that gives the model the ability to be suitable to most of the drilling applications in different well environments.

The hydraulic model requires data communication and database to secure the data transportation needed for the controllers. Many of data communications, database types and specifications discussed in section 4.6 of this chapter.

The other requirements of the hydraulic model design are the PLC and PID controllers. PLC and PID controllers discussed in chapter 3 briefly. They required an algorithm and logic associated to the model specifications and requirements that build up the order structure to regulate and switch the suitable valves and gates relation to the operation. PLC sends the needed information through the algorithm to the PID to control the valves and gates in the choke manifold and backpressure pump.

The PID controller required tuning to regulate the choke position set point that depends on many hydraulic parameters such as flow rate, geometry of the well, mud properties, and the hydraulic system compressibility. The response of the system depends on the tuning quality of the PID; therefore, the PID needs to be tested to check the response quality before using the PID in the operation.

One of the useful methods used to design a well is run a simulation for a prototype drilling wells by using the required well data to ensure the well design and the drilling hydraulic model to avoid or minimize the fault may happen during the operation. This kind of simulation called offline simulation.

Detecting of fault in the model related to the sensors used in the well as a pressure while drilling PWD sensors that depends on the position of the sensor that measure the pressure to compare the model results to the PWD sensor measurements. Furthermore, many other parameters measured that important for the operator in the semi-automated drilling operations.

4.2.1.1 Mathematical Model (Ulf Jakob F. Aarnes, 2011)

The drilling hydraulic model required a mathematical model represents the physical phenomena and calculate the required results depending on the mathematical equations, relationships and boundary conditions form these physical phenomena.

To build up a mathematical hydraulic model for drilling operation, it is necessary to make some assumptions to simplify the model. The reason behind simplifying the model is to ensure high performance for the model and eliminate or/and minimize faults in the model implementation that may lead to drilling problems.

The assumptions, generally, are:

- Newtonian fluid and viscosity
- Constant pump flow rate
- Constant pressure downstream of the choke
- Constant water density
- The hydraulic model derivation follows:
  - Fluid viscosity
  - Equation of state
  - Equation of mass
  - Equation of momentum Conservation of energy
- Laminar flow; Reynolds number equal or less than 2300
- Material properties are constant
- The pipe walls are rigid
- Thermodynamic effects are negligible
- Friction is a linear function of flow and estimated by using Herschel- Buckley method.

The mathematical hydraulic model required a control model treating mathematically the parameters effecting on the drilling operation. This mathematical model is as following: (John-Morten Godhavn, 2011)

$$\frac{V_d}{\beta_d} \dot{P}_p = q_p - q_{bit}$$

$$M\dot{q}_{bit} = P_p - P_c - F(q_{bit}, \omega_d) + (\rho_d - \rho_a)gh_{dh}$$

$$\frac{V_a}{\beta_a} \dot{P}_c = q_{bit} + q_{bpp} - A_d v_d - q_c + q_{err}$$

$$q_c = K_c\sqrt{P_c - P_{c0}}\, G(u_c) \qquad (1)$$

$$P_{dh} = P_c + \rho_a g h_{dh} + F_a(q_{bit}, \omega_d) \qquad (2)$$

The control goal formulized then as:

$$\left|P_{dh}(t) - P_{dh}^{SP}\right| \to 0 \text{ as } t \to 0 \qquad (3)$$

The estimate downhole pressure is given by:

$$\hat{P}_{dh} = P_c + \rho_a g h_{dh} + \hat{F}_a \qquad (4)$$

The choke pressure corresponding to the downhole pressure set point is given by:

$$P_c^{ref} = P_{dh}^{SP} - \rho_a g h_{dh} - \hat{F}_a \quad (5)$$

The chock pressure controller makes the choke pressure follow its reference:

$$\left|P_c(t) - P_c^{ref}(t)\right| \to 0 \quad (6)$$

If the choke pressure controller achieves this goal and the downhole estimator provides accurate estimates of the frictional pressure drop, i.e.

$$\left|\hat{F}_a(t) - F_a(t)\right| \to 0, \quad (7)$$

Then, as follows from (2), (5), control goal (3) is achieved.

4.2.2.2 Structural model

As the modeling definition in section (4.1), that the model could be a graphical structure as shows in fig. (4.3):

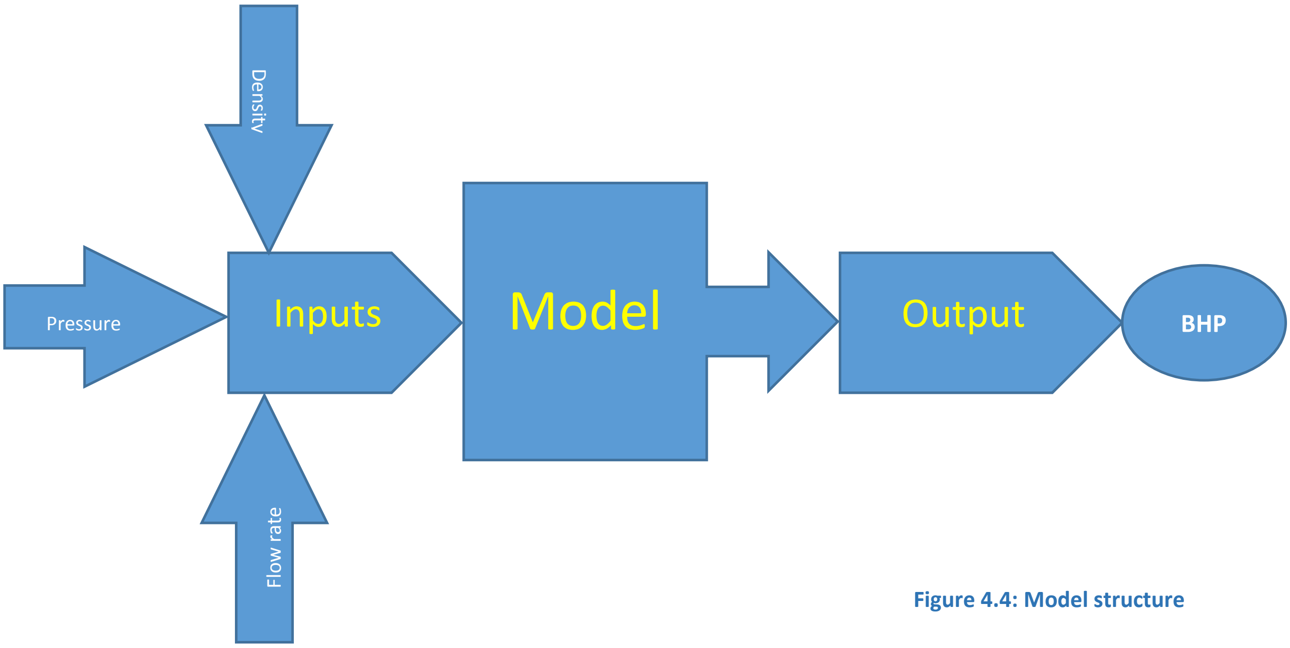


Figure 4.4: Model structure

The model inputs are:

- Flow rate
  - Choke flow rate q_c
  - Bit flow rate q_{bit}
  - Backpressure flow rate q_{bpp}
  - Pipe flow rate q_p
- Density
  - Drill pipe fluid density ρ_d
  - Annulus fluid density ρ_a

While the model output is the bottom hole pressure BHP.

4.2.3 Rheology and density model (Shifeng Tian, 2007) (SPE, IADC, 2014)

Rheology and density are very important parameters in the drilling operations that have relatively high effect on the well design in many aspects such as drilling program, drilling fluid design, well plug & abandonment, hole cleaning and many other things related to rheology and density. Rheology and density have a direct impact on the hydraulic model by effecting the wellbore pressure. Therefore, it is very important to take rheology and density parameters in consideration.

4.2.3.1 Rheology parameters effect

Mud (the drilling fluid) rheology parameters effect the well pressure in a way make it changes in value because of the fluid rheology specification. In drilling, there are three types of mud used as drilling fluids that are water based mud (WBM), oil based mud (OBM) and synthetic based mud (SBM). All these types currently used in drilling fields have what called non-zero yield point (YP).

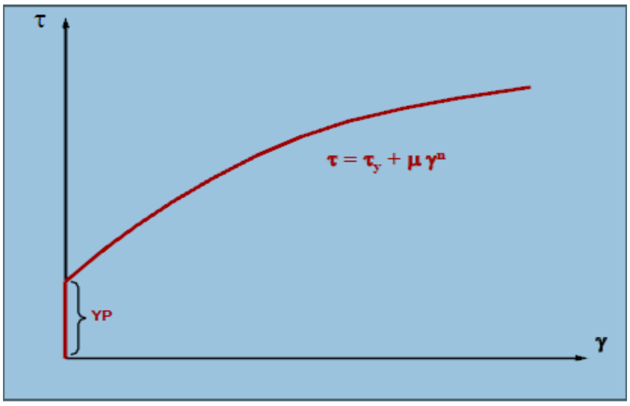


Figure 4.5: The relationship between shear stress and shear rate for a non-Newtonian fluid that has a non-zero yield point

Yield point is the point presents the distance on the shear stress τ the fluid start to yield (shear stress increasing with shear rate) as fig (4.4) shows the yield point that can estimated by Bingham Plastic model or by Herschel-Buckley model. This point/distance equal to zero for the Newtonian fluids and more than zero for non-Newtonian fluids such as (WBM, OBM or SBM), which have non-zero yield point.

This non- zero yield point cause sudden change in the bottom hole pressure (BHP) when the fluid start moving and when the fluid stop moving. The same thing happen when the drill string tripping out and tripping in regardless the tripping velocity. The BHP variation considered as a drilling problem.

The yield point YP estimation is difficult in the field because of the correct reading of YP can just be reached at a very low rotation speed RPM that is 3 rpm or less, which is not practically possible in the field.

The effect of fluid rheology on the drilling operation in different stages

- During drilling: one of the parameters effecting the BHP in the well is the frictional pressure that must controlled to keep the BHP constant. The frictional pressure controlled by two ways. The first way, by change the rheology of the fluid to keep the BHP in the drilling window between maximum pore pressure and minimum fracture pressure. This is a risky way in case of alteration of the fluid rheology take the BHP out of drilling window that leads to big and dangerous drilling problems. The other easy and fast way is to regulate the circulating rate to change the friction pressure that keeping the BHP in the drilling window.

- During connection: in this case, the effect of YP will clearly arise on the well pressure. When the pump stop, the fluid friction increase, which increase the equivalent mud weight EMW that require injecting backpressure in the annulus to reduce it. Increase of the EMW increases the YP effect with start circulation again. The effect of the YP on the BHP explained before that cause a pressure jump that usually hard to reduce. This pressure jump needs to be controlled by regulating the bake pressure simultaneously with the circulation rate that could be verified by regulate the choke and the pump carefully with a full cooperation between the choke and the pump operators.
- During tripping: regulating the BHP pressure during tripping required to add a heavier mud to the well to balance the surface choke pressure. This process will cause an YP pressure jump that required the same procedure as that during connection.

4.2.3.2 Rheology model

There are four types of rheology model relating to study the behavior of drilling fluid during the drilling operation to simplify the select process of the drilling fluid. The models relating parameters to the drilling operation as well are:

- Viscosity
- Shear rate
- Shear stress
- Gel strength
- Plastic viscosity PV
- Yield point YP
- Mud type
    - Mud selection
    - Additives
    - Preparation of drilling fluid

The four-used model in the industry are

- Newtonian model
- Bingham Plastic model
- Power Low model
- Herschel- Buckley model

Newtonian model

$$\tau = \mu . \gamma \quad (1)$$

Where τ is shear stress, μ is marsh funnel viscosity, and γ is the shear rate.

The model depends on the readings of the rheology experiment of Newtonian model for every rotation speed as the table (4.1) shows:

RPM (R)	**Reading (θ)**
600	10.5
300	7.5
200	7
100	6
6	4
3	3.5

Table 4.1: Shear stress in field units. (Kumar, 2010)

Then, these reading transferred to the field value depends on the following formulas:

$$\gamma = 1.703 \text{ V} \tag{2}$$

$$\tau = 1.607 \text{ R} \tag{3}$$

Then, according to the results for γ & τ obtained for each reading, we can plot the Newtonian fluid Rheogram as fig (4.5) shows:

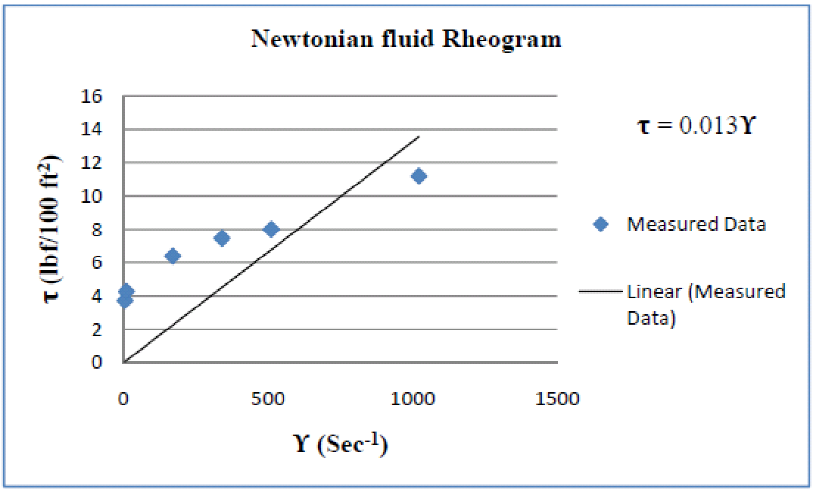


Figure 4.5: Newtonian fluid Rheogram. (Kumar, 2010)

To estimate viscosity in field units (cP), must converted by:

$$\mu = 47880 \text{ m}/100 \tag{4}$$

Then, estimating the EAAP, by using the statistical method between the measured and calculated shear stress, as following:

$$EAAP = [(1/N)\sum\{(\tau_{measured} - \tau_{calculated})/\tau_{measured}\}] \times 100 \quad (5)$$

Then, plotting the relationship between the measure and calculated results, as fig. (4.6) shows:

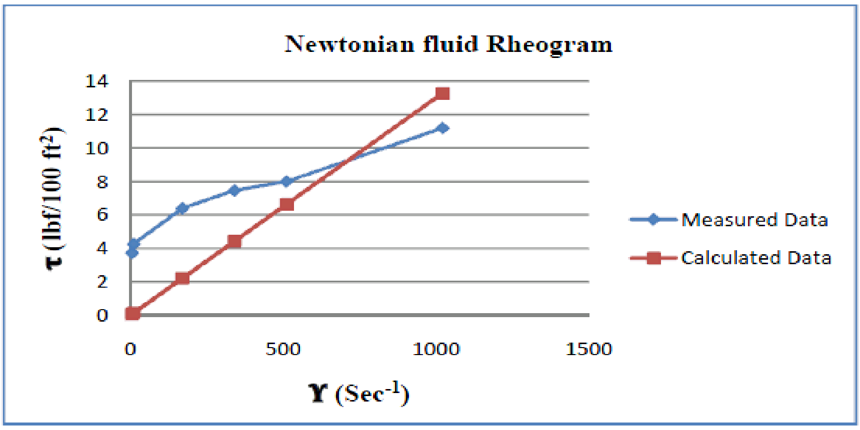


Figure4.6: Measured and calculated data comparison. (Kumar, 2010)

Bingham Plastic model

This model using the following formula:

$$\tau = \mu_p\,\gamma + \tau_Y \quad (6)$$

Eq. (6) can be wrote in another way, as following:

$$\tau = PV.\gamma + YP \quad (7)$$

Where PV is the plastic viscosity and YP is the yield point. Yield point and plastic viscosity and be read from a graph or can be calculated by:

$$PV = R_{600} - R_{300} \quad (8)$$

$$YP = R_{300} - PV \quad (9)$$

Figure (4.7) shows the Bingham Plastic fluid rheogram depending on the same data calculation used in the Newtonian model.

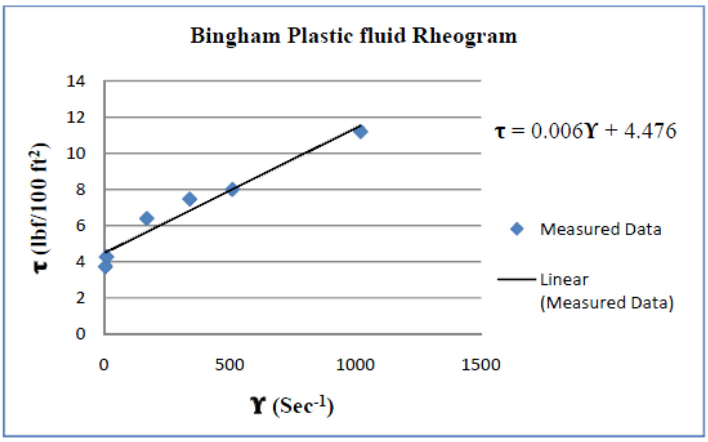


Figure 4.7: Bingham plastic model. (Kumar, 2010)

By using eq. (6) or (7), the shear stress calculated and the relationship between the measured and the calculated values plotted, as figure (4.8) shows:

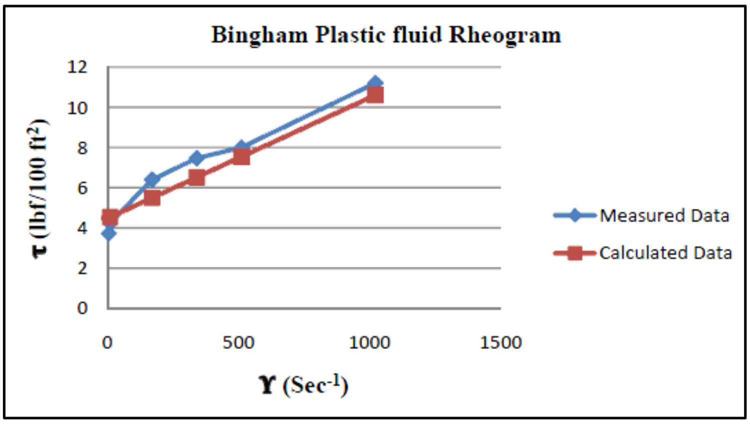


Figure 4.8: Measured and calculated comparison for the model. (Kumar, 2010)

Power Low Model

This model using the following formula to calculate the shear stress:

$$\tau = k\,\gamma^{n} \qquad (10)$$

Where K is the consistence index and n is the flow behavior index.

Using the following formula to linearized eq. (10):

$$\log\tau = \log k + n\ \log\gamma \qquad (11)$$

Where n determined from the slop and k is the intercept. Figure (4.9) shows the Power Low fluid Rheogram.

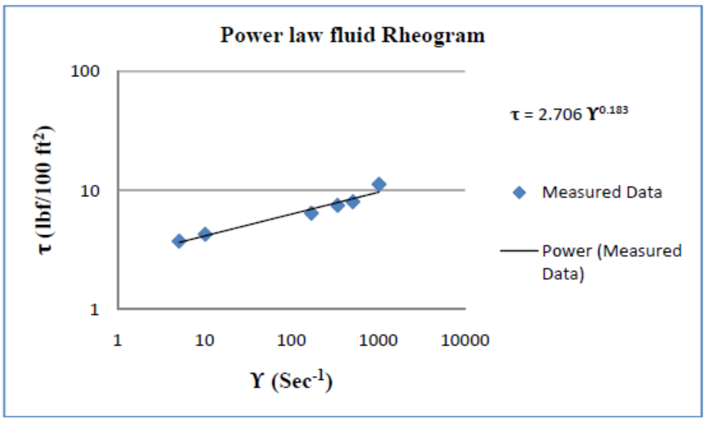


Figure4.9: Power Low Fluid Rheogram. (Kumar, 2010)

Using eq. (5) to calculate EAAP and plot the comparison between the calculated and measured values, as shown in figure (4.10):

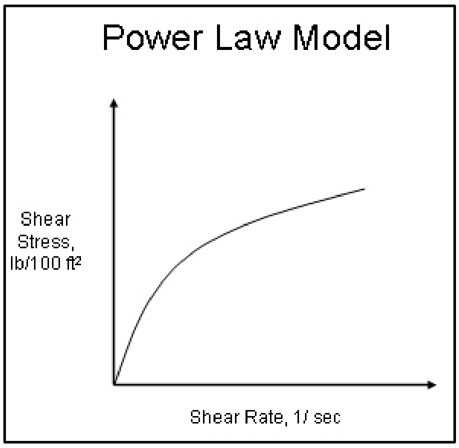


Figure 4.60: Measured and calculated values comparison of the model. (Kumar, 2010)

The values of n & k estimated by the following formulas:

$$n = 3.32\ \log\left(\frac{R_{600}}{R_{300}}\right) \tag{12}$$

$$k = 510\left(\frac{R_{600}}{511^{n}}\right) \tag{13}$$

Herschel-Bulkely Model

The formula used in this model is:

$$\tau = \tau_0 + k\gamma^{n} \tag{14}$$

$$\log(\tau - \tau_0) = \log(k) + n\ \log(\gamma) \tag{15}$$

$$\tau_0 = \frac{\tau^{*2} - \tau_{min} \times \tau_{max}}{2 \times \tau^{*} - \tau_{min} - \tau_{max}} \tag{16}$$

$$\gamma^{*} = \sqrt{\gamma_{min}\gamma_{max}} \tag{17}$$

Where τ^{*} is the shear stress value corresponding to the geometric mean of the shear rate. Figure (4.11) shows the Herschel-Bulkely Rheogram.

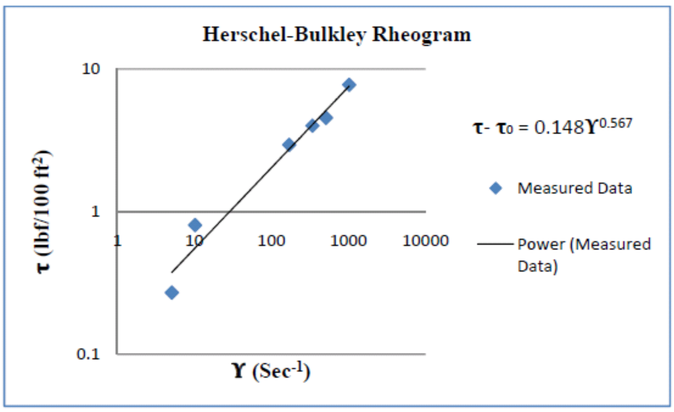


Figure 4.11: Herschel-Bulkely Rheogram. (Kumar, 2010)

Finding the parameters n & k from fig. (27) to calculate the shear stress and compared the result to measured values to plot figure (4.12) as shown:

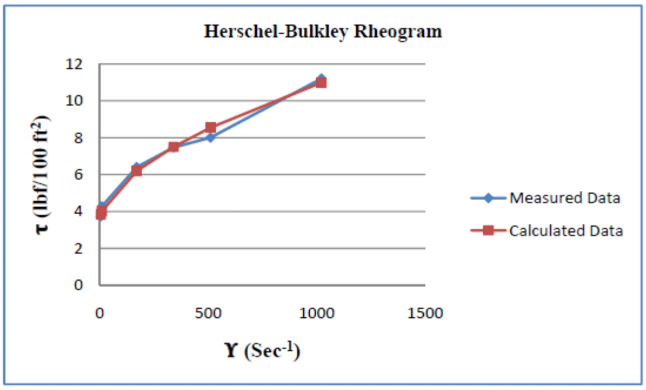


Figure 4.72: Comparison measured to calculated values for the model. (Kumar, 2010)

Generalized Reynolds number

The Fanning friction factor for the steady, stabilized, laminar flow defined as:

$f = 2\tau_w/\rho v^2$ (Metzner et al. 1955)

The wall shear stress formula of pipe flow can be obtained from a force balance principle,

Viz. $\tau_w = \Delta p D/(4L)$

Then we combined the wall shear stress formula with Fanning friction definition formula, viz. $f = 2\tau_w/\rho v^2$. And referenced to the formula related friction factor to Reynolds number for Newtonian pipe flow, vis. $f = 16/Re$, the generalized Reynolds number for H-B fluid can be obtained:

$$Re_{g,p} = \frac{\rho D v}{\left(\frac{2n'+1}{3n'}\right)\tau_w/\gamma_w} = \frac{\rho\left(\frac{4n'}{3n'+1}\right)Dv}{\tau_w/\gamma_w} = \frac{\rho D_{eff,a} v}{\tau_w/\gamma_w} \quad (18)$$

$$Re_{g,a} = \frac{\rho\left(\frac{2}{3}D_{hy}\right)v}{\left(\frac{2n'_a+1}{3n'_a}\right)\tau_w/\gamma_w} = \frac{\rho\left(\frac{2}{3}\frac{3n'_a}{2n'_a+1}\right)v}{\tau_w/\gamma_w} = \frac{\rho D_{eff,a} v}{\tau_w/\gamma_w} \quad (19)$$

Reed and Pilehvari (1993) gave the expression of apparent viscosity as $\mu_{w,app} = \tau_w/\gamma_w$. Then the generalized Reynolds number for the pipe and annuli can be rewrite as:

$$Re_g = \frac{\rho D_{eff} v}{\mu_{w,app}} \quad (20)$$

In summary of the preceding paragraph, it is clear that both pipe and annular flow for H-B fluid linked to the Newtonian fluid pipe flow based on the generalized effective diameter and generalized Reynolds number.

Pressure loss calculation

The next step is to obtain the Fanning friction factor relating to Reynolds number. The laminar flow Fanning friction factor for both pipe and annuli expressed as the following formula:

$$f = \frac{16}{Re_g} \tag{21}$$

The fanning friction factor for non-laminar flow used for the transient region and fully turbulent flow is a combination of Dodge-Metzner (Dodge et al. 1959) equation and Colebrook`s equation (Bourgoyne et al. 1991), which includes the roughness effect. The derivation performed by Reed and Pilehvari and the formula follows (Reed et al. 1993):

$$\frac{1}{\sqrt{f}} = -4\ \log_{10}\left\{\frac{0.27\varepsilon}{D_{eff}} + \frac{1.26\left(n^{`}\right)^{-1.2}}{\left[Re_g f^{\left(1-0.5n^{`}\right)}\right]^{n^{`-0.75}}}\right\} \tag{22}$$

Where ε is the absolute roughness. Thus, the pressure loss calculated by the following equation:

$$\Delta P = \begin{cases} 2f\frac{\rho v^2}{D}L & \text{(pipe flow)} \\ 2f\frac{\rho v^2}{D_{hy}}L & \text{(annular flow)} \end{cases} \tag{23}$$

Model structure in a block diagram as figure (4.13) shows:

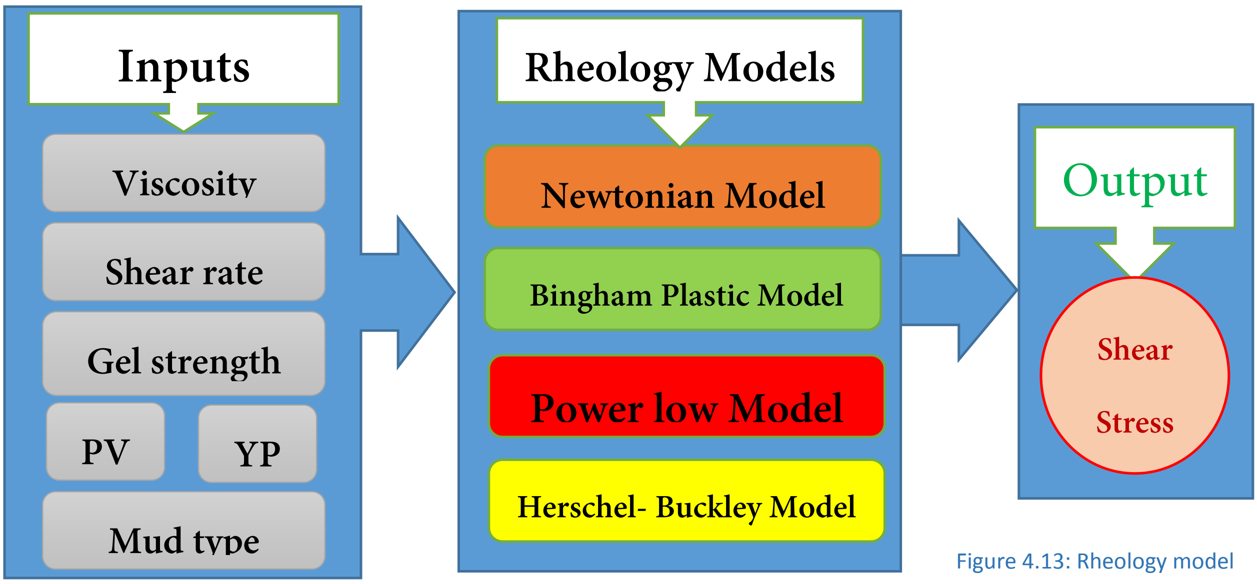


Figure 4.13: Rheology model structure

Model application in MPD operation

Rheology model has many industrial applications today, but the concern application in this thesis will be the rheological drilling applications. The model used in many fields as a monitoring for drilling hydraulics to compare the measurement with the modal results of calculations.

The model using divided segments in the well because of the length of the well and the drill string. This method used to ensure the real time monitoring by the model. The rheology model have been used in the constant bottom hole pressure method to MPD that realized that the back pressure can be adjusted precisely by using the H-B hydraulic model. The figures (4.14) & (4.15) show the results of using H-B hydraulic model to MPD.

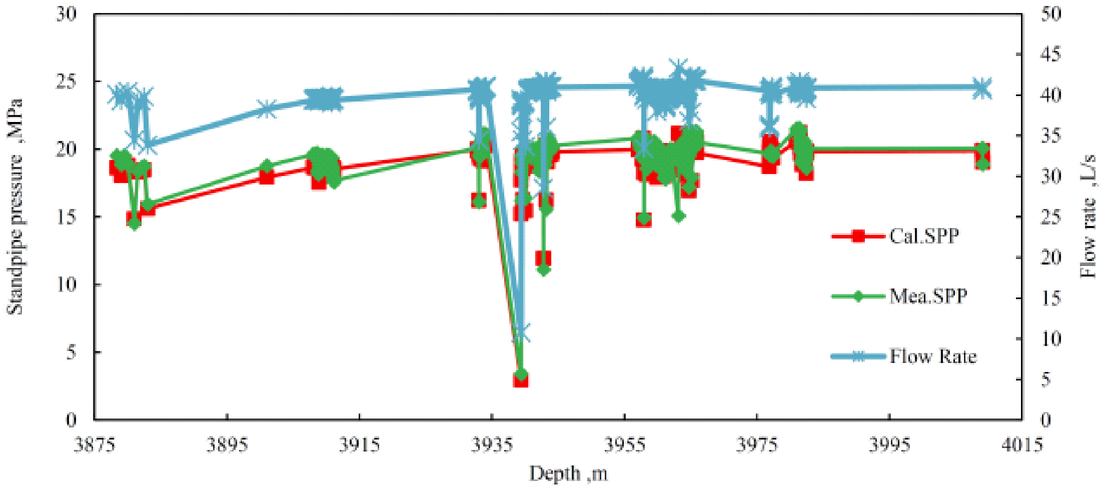


Figure 4.84: measured and calculated standpipe pressure. (SPE, IADC, 2014)

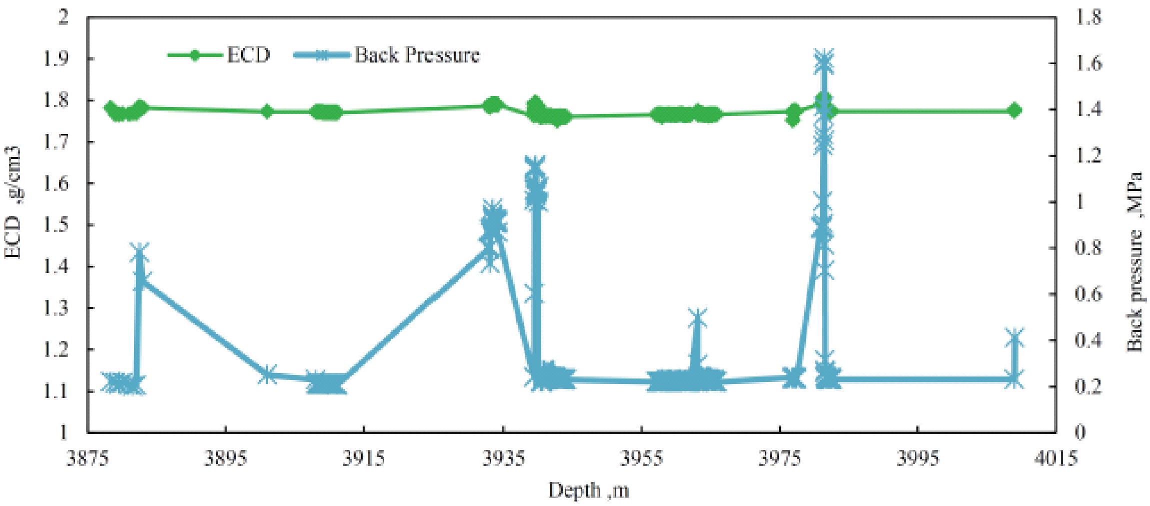


Figure 4.95: Bottom hole ECD and backpressure. (SPE, IADC, 2014)

4.2.3.3 Density parameter effect (Shifeng Tian, 2007)

Density is an important factor to control during drilling especially for MPD because of the direct effect of drilling fluid density on the drilling window that lies between the pore pressure and fracture pressure.

There are three types or names of density used in the drilling operations, which are equivalent mud weight (EMW), equivalent circulating density (ECD), and equivalent static density (ESD). EMW related to the hydrostatic pressure downhole at the static situation, while ECD related to the dynamic situation, but both referring to the backpressure effect on the surface pressure considering the effect of the friction of the circulating fluid.

The most effective factor on fluid density is compressibility that increases with depth and temperature. This effect can easily detected by the density difference between the same fluid in the pit at the surface and at a considerable depth and temperature that practically reach to 0.5 ppg difference. This will leads to effect the effective hydrostatic head additional to the other factors such as backpressure and cuttings density. Figure (4.16) shows the mud density in a drilling window.

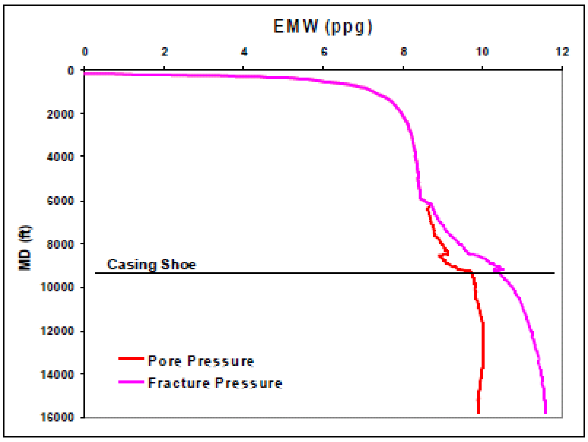


Figure 4.16: Density effect on drilling window. (Shifeng Tian, 2007)

4.2.3.4 Density Hydraulic model

There are many parameters effected the drilling operation and the well pressure during this operation such as:

- Fluid density
- Fluid rheology
- Temperature in the pipe and the annular
- Pumping rate RPM
- Casing and drill string specifications
- Cutting transport

All these parameters effecting each other and effect the whole drilling operation, so it is necessary to calculate and monitor all these parameters during drilling to ensure an effective and safe drilling operation.

One of the models used for fluid density is Robertson-Stiff model that mainly discuss the temperature effect on most of these parameters end specially the fluid density. The model results used to confirm the real time data on the practice.

The general concept of using a simulation fluid density model is the narrow drilling window for the MPD operation that is difficulty of choosing the suitable mud density for the operation. The advantage of this simulation/ model are

- Gives precise details for wellbore hydraulic analysis
- Guide the drilling engineer in decision making through different drilling scenarios.
- Helps to select the suitable drilling equipment
- Guide the driller to choose the right fluid densities during the drilling operation

The only disadvantage of Robertson-Stiff model is the procedure complicity because of the effect of the parameters on each other such as the contrary effect of temperature and pressure on the fluid density, the differences in effect of heat exchanging during static and dynamic drilling situation as fig. (4.17) and fig (4.18) show for the temperature distribution in the well at the static and dynamic drilling situation.

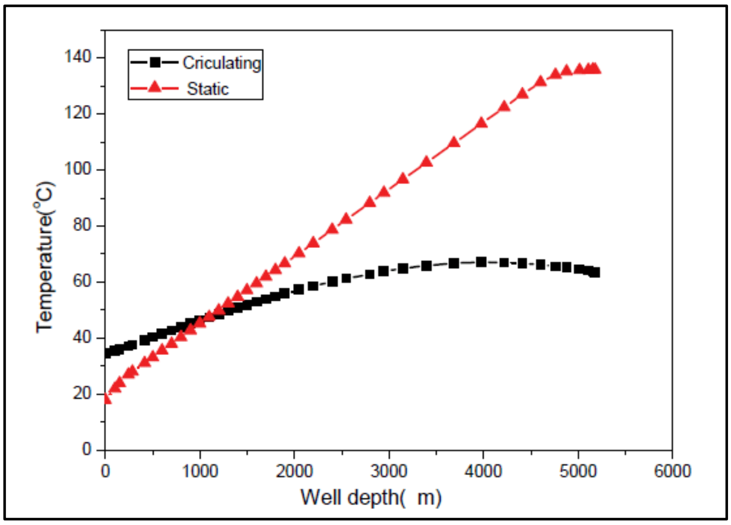


Figure 4.107: Static drilling temperature distribution. (SPE, 2010)

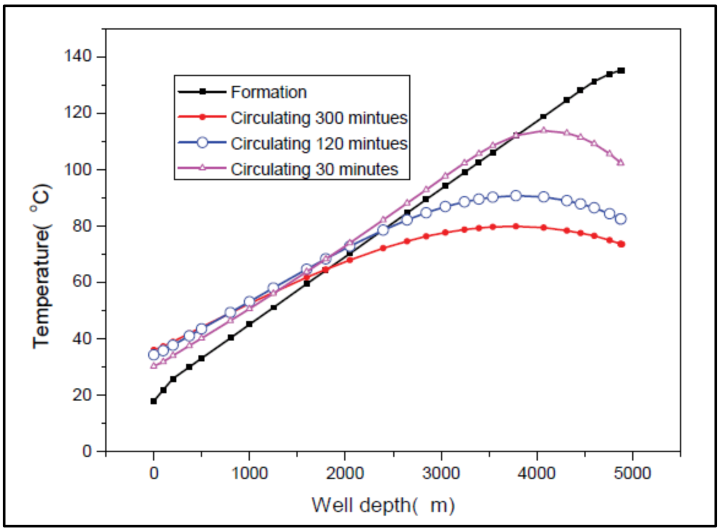


Figure 4.118: Dynamics drilling temperature distribution for different circulation time. (SPE, 2010)

The model assume some assumptions to calculate the mathematical differential equations required for the model:

- ✓ The axial conduction of heat in the fluid is negligible compared with axial convection
- ✓ No radial gradient in the fluid both in the pipe and the annular
- ✓ Heat generation by viscous dissipation in fluid is negligible
- ✓ The flow is one dimensional steady flow
- ✓ The temperature and pressure are the same in one section
- ✓ The wellbore heat transfer is steady state
- ✓ The heat transfer of formation around the wellbore is non-steady state

The model expressed by the following equations:

$$\rho_w(P,T) = \rho_0 e^{(C_1(T-T_0)+C_2(T-T_0)^2+C_3(P-P_0)} \quad (1)$$

Where: $\rho_0 = 8.3619$ ppg

$T_0 = 59^{\circ}F$

$P_0 = 14.69$ psi

C_1, C_2 and C_3 are model parameters

Figure (4.19) shows the effect of temperature on the fluid density.

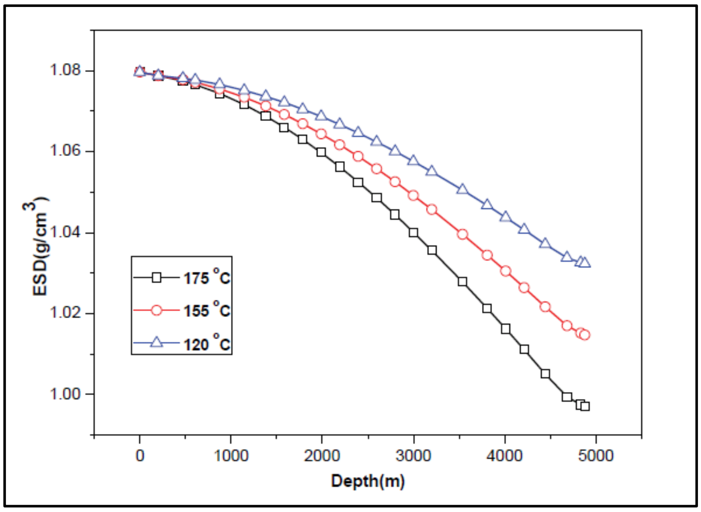


Figure 4.19: The temperature effect on the drilling fluid density. (SPE, 2010)

Figure (4.20) shows the density model structure illustrating the input parameters to the model, and the result given by the model

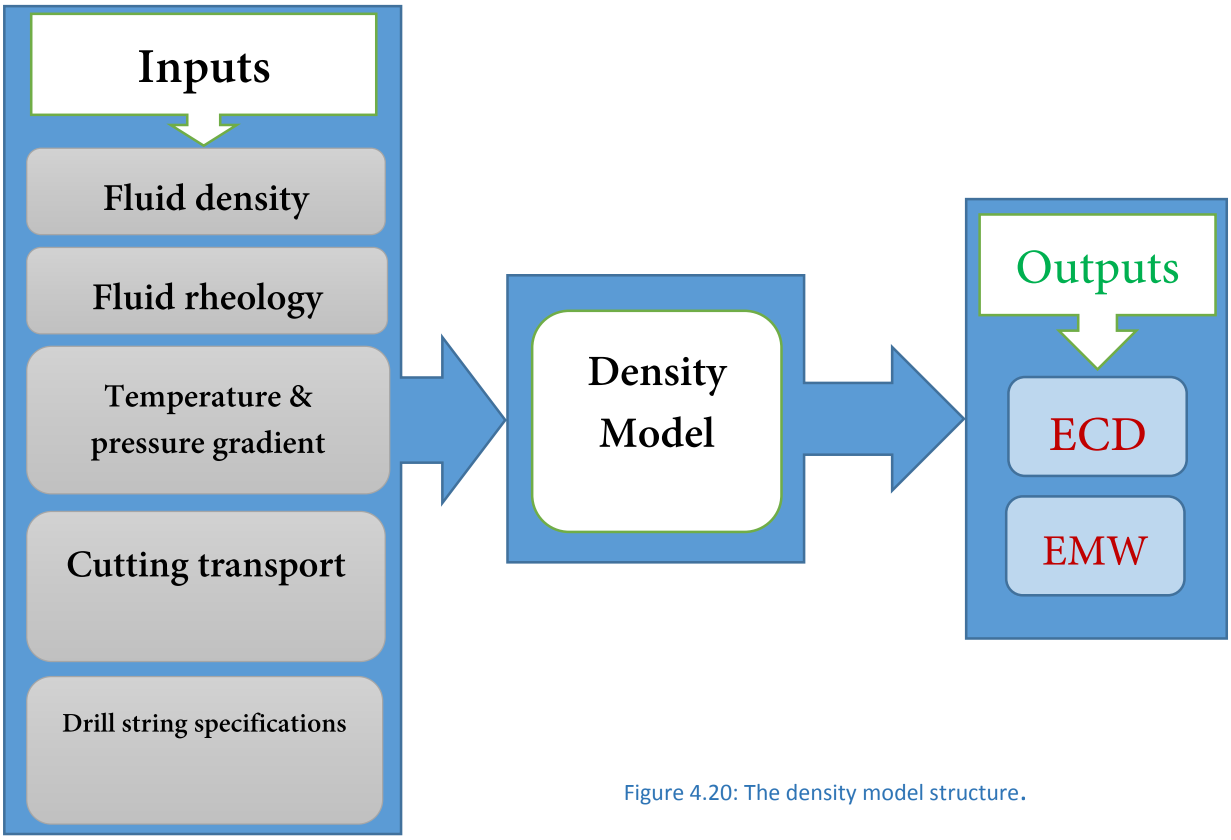


Figure 4.20: The density model structure.

4.2.4 Hole cleaning effect on drilling (AADE, 2008)

Hole cleaning is a function of

- Well profile and geometry
  - Hole angle and doglegs
  - Hole/tubular geometry
  - Drill string eccentricity
- Cutting and cuttings-bed characteristics.
  - Specific gravity
  - Particles size and shape
  - Reactivity with mud
- Flow characteristics
  - Annular velocity and profile
  - Flow regime
  - Flow rate
- Mud properties
  - Mud weight
  - Viscosity
  - Gel strength
- Drilling parameters
  - Bit type
  - Rate of penetration ROP
  - Differential pressure
  - Pipe rotation
  - Pumping rate

The parameters mentioned above divided, according kind of effect, into two groups

- Parameters effecting the particles properties such as size, weight and material properties.
- Parameters affecting the particles transportation.

The most important parameters effecting the hole cleaning as a result of all the above parameters are annular velocity and viscosity.

Settling velocity playing a main role of effecting on the hole cleaning efficiency negatively. Three particle-settling mechanisms are the most known types today, which are:

- Free settling that depending on the density difference between the fluid and particles
- Hindered settling that mitigating the slip velocity that increases cutting settling
- Boycott settling that discovered by a physician who found this type of settling. This type related to the deviated holes that cause settling acceleration.

The drill cutting characteristics with help of many other parameters may increasing the cutting settling in case of not taking a step of remove cuttings that will leads to cuttings accumulation, which leads at the end to poor hole cleaning that leads to many drilling problems such as stuck up, twist off and so on.

Flow characteristics playing an important role in hole cleaning that depends on the annular velocity and the profile of the annular velocity. The figures (4.21) & (4.22) show the annular velocity distribution when the drill pipe concentric and eccentric respectively.

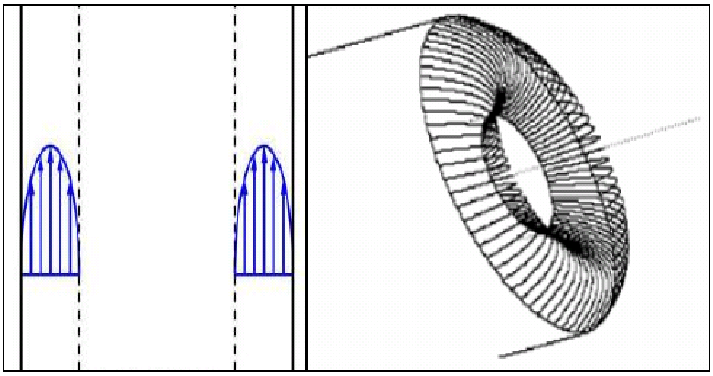


Figure 4.121: Annular velocity distribution in a concentric drill pipe. (Rahimov, 2009)

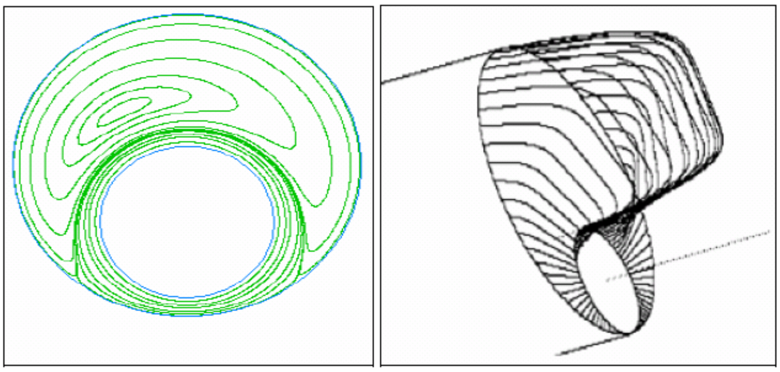


Figure 4.13: Eccentric drill pipe velocity distribution (Rahimov, 2009)

Fig. (4.21) shows the ideal annular velocity distribution that is rarely exist in drilling, while fig. (4.22) shows the typical annular velocity distribution in a drilling operation because most of wells is not completely vertical.

The hole cleaning is directly proportional to the velocity distribution at suitable annular velocity, but when the annular velocity becomes minimal, the cuttings will accumulate at the low side of the hole that required an enough drill string rotating speed to move the cuttings upward to transport it out of the well.

Mud properties have different effect on hole cleaning, where mud density according to buoyancy relationship leads to buoying cuttings and slow down the settling velocity, but it is not the main role of mud density to be chosen for hole cleaning improvement than other functions related to well stability. While the viscosity playing an important role in hole cleaning.

Cutting transport ratio (CTR) is the ratio between transport velocity and annular velocity, as following:

$$\mathrm{CTR\%} = \frac{V_r}{V_a} \qquad (1)$$

Where, V_r is transport velocity, V_a is the annular velocity. Transport velocity is the difference between the annular velocity and the slip velocity as given:

$$V_r = V_a - V_s \qquad (2)$$

Where V_s is the slips velocity. The transport just used for a vertical wells and it is an indication for effective hole clean55ing if the transport velocity is close to or equal to the annular velocity.

CTR its gravity force. The slip velocity V_s given by the following formula:

$$V_s = 138\frac{d_p^2(\rho_p-\rho_f)}{\mu} \quad (3)$$

Where d_p the particle diameter, ρ_p the particle density, ρ_f the fluid density, and is the viscosity. There are many correlation methods used to correlate the slip velocity for different drilling situations, but it is not the thesis part of concern.

According to some simulation study (Okabe, 2014) the cutting bed has a significant effect on the value of ECD specially in the ERD drilling especially at inclined wells and horizontal wells. Figure (4.23) shows the simulation model of hole cleaning study.

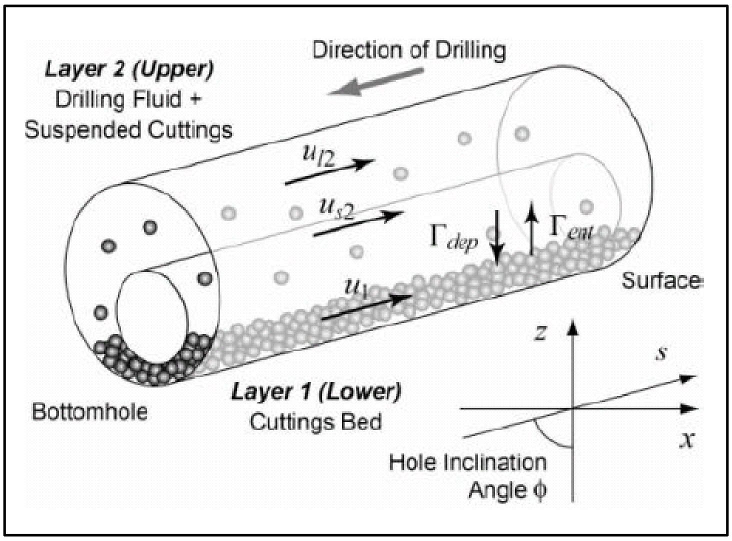


Figure 4.143: Flow model for a simulation study concern of the effect of hole cleaning on ECD (Okabe, 2014)

The simulation the correlation of coefficient of friction for different cutting Reynolds number and gives some recommendations about the suitable annular velocity to ensure increasing cutting transport velocity, and reducing the cutting bed by choosing the suitable mud density and viscosity.

The general improvement of the hole cleaning depends on regulating some parameters such as reducing the flow rate, reduce solids/cuttings in the annular, controlling rate of penetration ROP, and run back reaming before connection.

Figure (4.24) shows the rheology model structure:

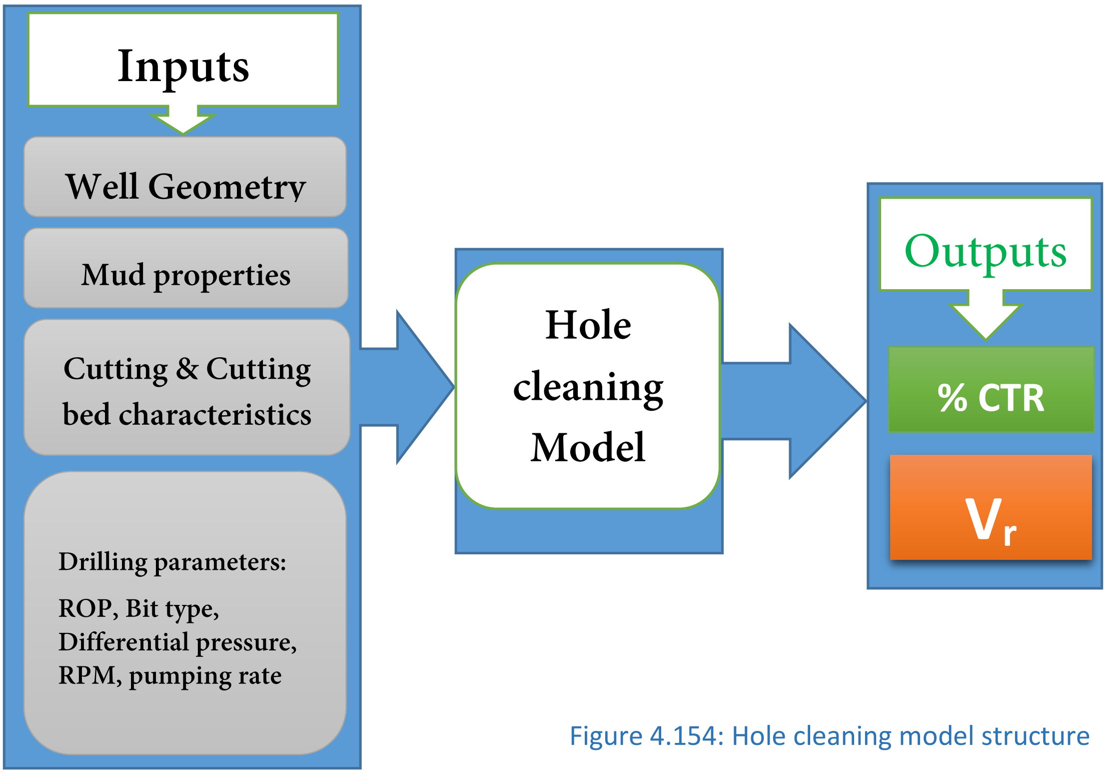


Figure 4.154: Hole cleaning model structure

4.2.5 Torque and drag model

The general definition of torque is the force multiplied by the radius r of a pipe required to rotate the pipe. In drilling, torque is the moment required to rotate the drilling pipe and this moment is equal to the force-acting tangent to the pipe circumstance, against any other reverse force, multiplied by the radius of the pipe.

The drag force is the force required to move the pipe up and down in the well against any other force such as the weight of the drill pipe, the friction force and so on.

During drilling, tripping in and tripping out the combination of high drag and high torque may leads to many drilling problems specially in difficult wells such as high deviated wells, dogleg, HPHT wells and so on. The parameters effecting torque and drag are:

- Mud type
- Formation properties
- Hydrodynamic viscous force
- Fluid density difference during tripping inn
- Pore hole cleaning
- Wellbore instability
- Differential sticking
- Loss of circulation
- Pipe and BHA stiffness
- Drill string weight

- Surface roughness
- Contact surface
- Doglegs
- Key seating
- Tortuosity

4.2.5.1 Friction and friction factor effect on torque and drag model

It is important to notice that friction and friction factor is the most effective parameter on the torque and drag model. There are two states of friction, static friction and dynamic friction. The static friction neglected, but the dynamic friction taken in concern in the model and it assumed constant. The friction factor given as:

$$\mu = \frac{F_f}{F_n} \qquad (1)$$

Where μ the friction coefficient/factor, F_f the friction force, and F_n the normal force as figure (4.25) shows the forces acting on a sliding plane. The friction force is the force between the block and the inclined plane parallel to the normal force. Friction coefficient vary according to the plane roughness, fluid type, formation type, and composition and lubrication.

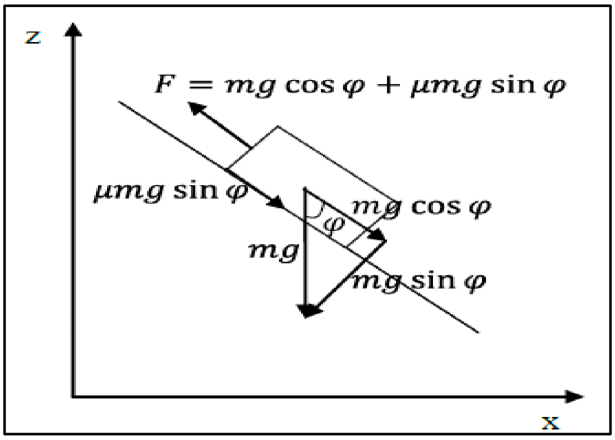


Figure 4.165: Forces acting on a sliding plane. (Tveitda, 2011)

4.2.5.2 Buoyancy factor

Archimedes principle is the principle standing behind the buoyancy factor for the drill string buoyance in the drilling fluid during the drilling operation, which given as:

$$\beta = 1 - \frac{\rho_{mud}}{\rho_{string}} \qquad (2)$$

Where β the buoyancy factor, ρ_{mud} the mud density, and ρ_{string} is the string density. This factor gives the ability of find the weight of the pipe immerged in the fluid by multiplying the buoyancy factor by the weight of pipe at air.

If there are more than one fluid inside and outside the drilling pipe (e.g. during tripping inn and out), the fluids density have to be accounted in the formula as following:

$$\beta = 1 - \frac{\rho_o A_o - \rho_i A_i}{\rho_{string}(A_o - A_i)} \qquad (3)$$

Where ρ_o the fluid density outside the drill pipe, $A_o$the cross section area outside the drill pipe, ρ_i the fluid density inside the drill pipe, and $A_i$the cross section area inside the drill pipe.

4.1.5.3 Wellbore trajectory

Wellbore trajectory, practically, unknown exactly because of the complicity of the drilling bath and uncertainty of the measurement tools. The wellbore trajectory depends on measurements and calculations. The measurements depends on some definitions such as the well inclination, the well azimuth, and the measured depth between two surveys.

The inclination angle (ϕ) is the angle between vertical and the tangent to the wellbore, and then the inclination angle is zero for a vertical well and 90 degree for a horizontal well.

The azimuth (α) is the angle between true north and the tangent of the wellbore.

The survey is the measurement technique called measurement while drilling for the well downhole to measure the inclination and the azimuth of the well.

The calculations made based on the measurements to find the parameters required for the torque and drag model such as:

- The true vertical depth TVD
- Dogleg DL
- Dogleg severity DLS

$$\theta = \cos^{-1}[\sin\varphi_1 \sin\varphi_2 \cos(\alpha_1 - \alpha_2) + \cos\varphi_1 \cos\varphi_2] \qquad (4)$$

Where θ is absolute angle of direction.

$$R = \frac{\Delta L}{\theta} \qquad (5)$$

Where R is the radius of a bend, and ΔL the distance between two positions.

$$DL = \frac{180|\theta|}{\pi} \qquad (6)$$

$$DLS = \frac{DL}{\Delta L}30 \qquad (7)$$

Figure (4.26) shows the torque and drag model structure:

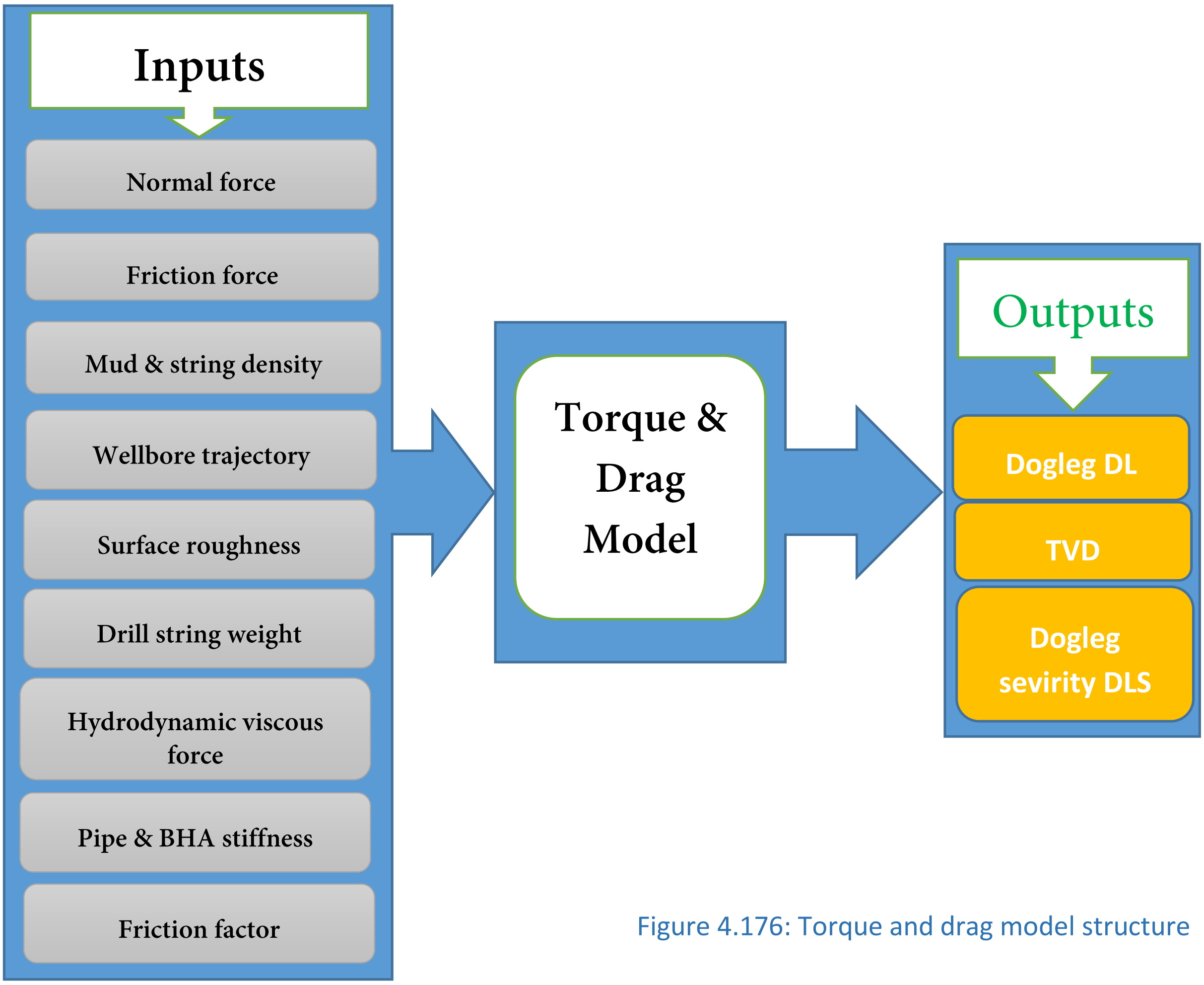


Figure 4.176: Torque and drag model structure

Hole cleaning effecting highly torque and drag in a way of poor hole cleaning leads to cutting accumulation that will increase torque and drag, and good hole cleaning reduce torque and drag in the well. Cutting transport depends on many factors such as

- Well inclination angle
  - From 0-35 degree: good cutting transport
  - From 35-50 degree: partially settle of cuttings that required continuous drill string rotation and pumping to ensure good hole cleaning.
  - From 60-90 degree: leads to cutting bed hard to remove unless using higher hydraulic requirements to ensure hole cleaning.
- Annular flow velocity increasing cutting transport
- Viscosity reducing cutting transport efficiency and leads to pressure instability.
- Rotational speed increasing cutting transport.

4.2.5.5 Buckling

Buckling is a very important factor for torque and drag model because of the additional force occurs between the wellbore wall and the pipe. Figures (4.27) & (4.28) show the sinusoidal buckling and the helical buckling respectively.

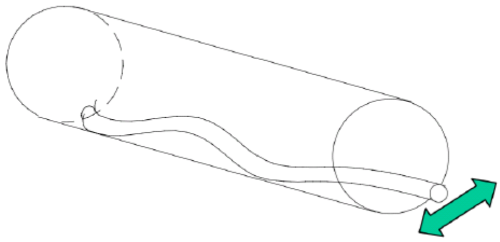


Figure 4.187: Sinusoidal buckling (Tveitda, 2011)

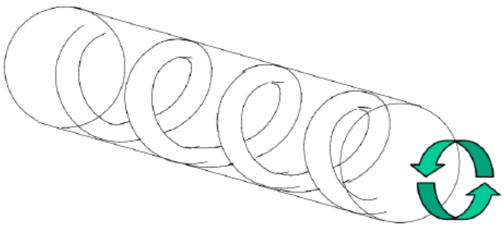


Figure 4.198: Helical buckling. (Tveitda, 2011)

Sinusoidal buckling considers as a first order buckling that cause a lateral force between the drill pipe and the wellbore hole, while the helical buckling considered as a second order buckling that cause a rotational contact between the wellbore and the drill pipe, which much higher than the force caused by the sinusoidal buckling.

4.2.5.6 Standard torque and drag model and the new 3D model

This model created by Johancsik et al. (1984) based on the standard Coulomb friction model. The model starts from the bottom to the top with small segments to describe the behavior of the drill string in the well path. The model used to calculate the normal force between the pipe segment and the wellbore wall considering the connections between the segments and the tension and torsion forces applied by connections.

Figure (4.29) shows the model force analysis to calculate the normal force.

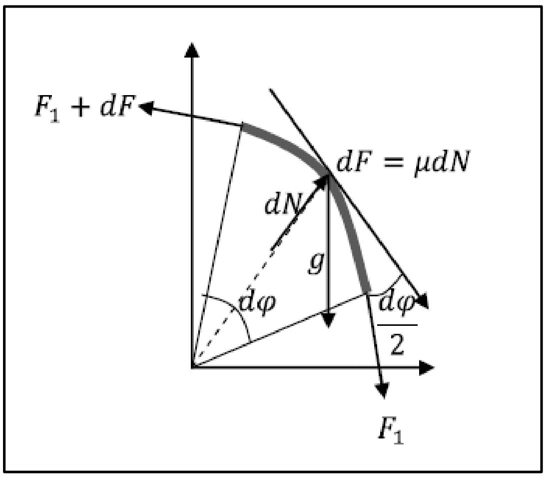


Figure 4.29: The model force analysis. (Tveitda, 2011)

There some disadvantage of the standard model that are:

- It is consider as a good model, not perfect and sometimes poor in performance.

- The friction factor assumed constant, while practically the friction factor might be different during tripping in and out, even it might be different for each trip.

The new 3D model is similar to the standard model in the straight section and differ from it in the curved section. The new model developed and simplified many times by different researchers such as Aadnoy, Anderson, Djurhuus, Fazaelizadeh, and Harelad etween 2008-2009. The model derivation depends on the absolute angle change in the straight section and the curved section that required two equations for torque and drag for each section. The model define the reaming and back reaming motion by Hook load in addition to the hoisting, static and lowering. Figure (4.30) shows the new 3D model.

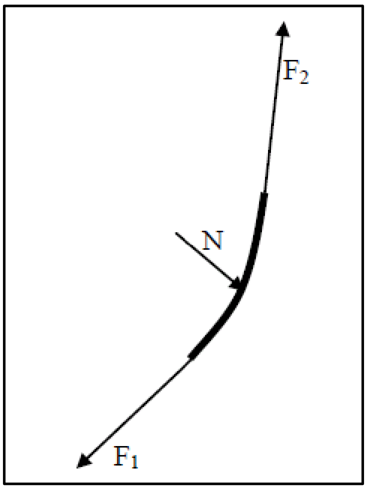


Figure 4.30: New 3D model. (Tveitda, 2011)

4.2.5.8 The effect of some other factors on the T&D model

There are some important issues effecting the T&D model such as:

- Hydrodynamic viscous force
- Mud circulation
- Rotation speed RPM

Circulation of mud effects the weight of the drill string based on the hole size, drill string size, mud rheology and pump rate. The is a force effecting on the T&D model called hydrodynamic viscous force, which depends on many parameters such as:

- Flow regime
- Fluid viscosity
- Annular velocity
- Temperature
- Drill string size and annulus size
- Rheology

The effect of the hydrodynamic viscous force occur especially at surge and swab situation during trip inn and out.

The effect of viscous drag is relatively small compared with the effect of RPM that leads to exiting the string and increasing torque to the level to occur vibration and whirl in the drill string. Such effect did not included in the model yet because of the complicity of the vibration phenomenon.

4.2.6 Pore pressure modelling

Pore pressure modeling is one of the two major components relating to well drilling cost and safety together to the wellbore stability. Pore pressure has a direct relationship to the rate of penetration because it depends on the difference between the bottom hole pressure and pore pressure.

The pore pressure in a well affected by the following parameters:

- Sediment accumulation
- Permeability
- Flow regime
- Geological events such as figure (4.31) shows

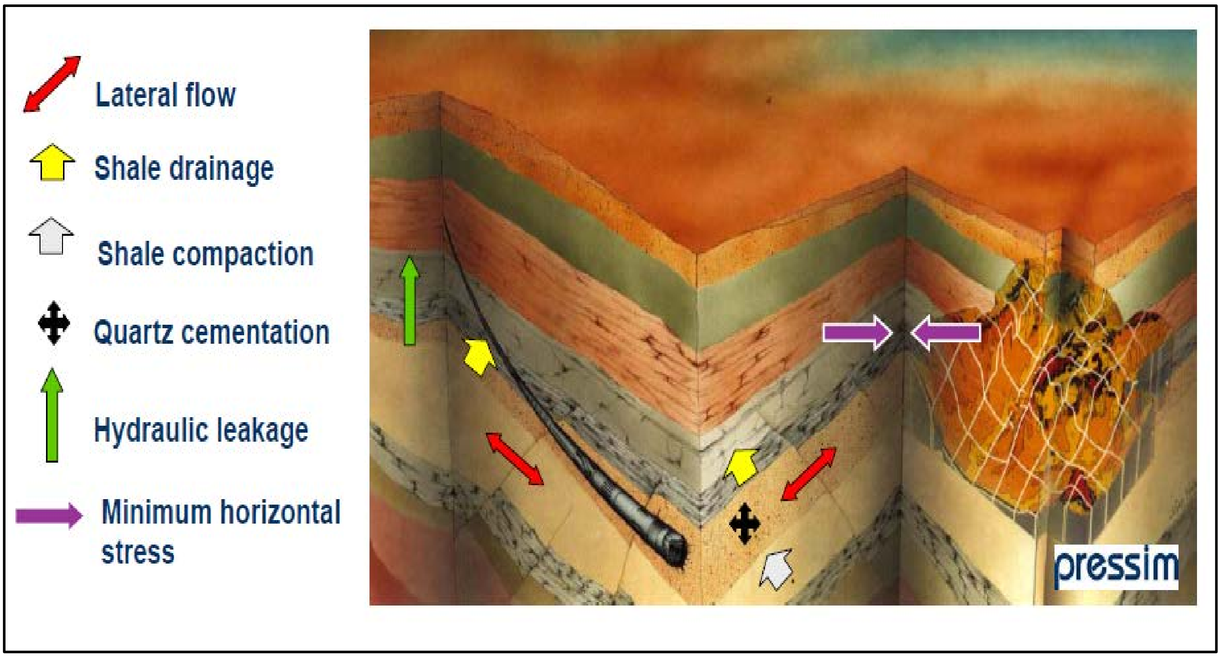


Figure 4.31: Geological events effect on pore pressure. (SPE, 2005)

There are many estimation methods of pore pressure, all divided into three steps:

- Predicting
- Detecting
- Real time evaluation and calibration

Predrilling, the pore pressure estimated by using geophysical methods such as formation velocity analyzing, and magnetic and electric data from the offset wells. While during drilling, all the measurement equipment and data used for pore pressure estimation such as:

- Logging while drilling data LWD

- Rate of penetration ROP
- Torque and drag measurements
- Drill ability
- D-exponent and modified d-exponent
- Logging interpretation (resistivity, density, porosity)

The pore pressure estimation using MPD data through MPD operation ensures:

- Management of annular pressure by regulating the surface backpressure by an automated chock.
- Monitoring return flow by using a Coriolis flowmeter
- Measuring the standpipe pressure (SPP) and surface backpressure (SBP) by a digital sensors.
- Dynamic formation integrity test (FIT) repetitively.
- Pore pressure test (PPT) without stop circulation.

MPD estimation method of pore pressure is more effective, accurate and economic than the use of the standard pore pressure estimation by the conventional Eaton estimation method. This method gives accurate results for Pore pressure and in case of gas influx or loss circulation. The continuous circulation system used in MPD with help of the MPD equipment manipulating the downhole pressure to keep it into the designed drilling window and estimate the pore pressure value by running the pore pressure tests dynamically, which called dynamic pore pressure test DPPT. Figure (4.32) shows a dynamic pore pressure test using MPD. While PPT used for estimation pore pressure, the FIT used for estimation the fracture pressure, so using PPT & FIT together gives the drilling window estimation that is important for the MPD operation both manually and automatically.

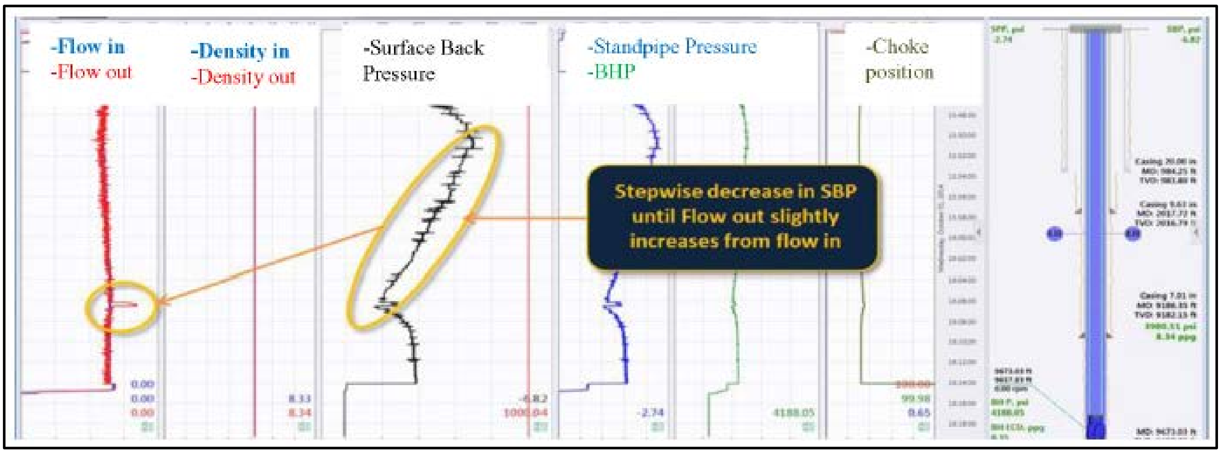


Figure 4.32: DPPT using MPD. (S. Ameen Rostami, 2015)

The pore pressure not always needs to be estimated where it just need to be measured indirectly. In the low permeability formations such as clay, shale, silt and mud, because the pore fluid is static and will not flow. While the high permeability formations such as sand and salt, the pore fluid may flow that, make it difficult/ impossible to measure directly. Using the dynamic pore pressure test calibrated with pore pressure measurement ensures pore pressure estimation in the high permeability formation section such as sand or shale-sand sections.

4.2.7 Rate of penetration ROP optimization

The rate of penetration ROP is the speed of the drill string with the drill bit through the formation in (m/h) unit. There are many factors affecting the rate of penetration ROP, such as:

- Bit type and bit wear
- Rotational speed RPM
- Weight on bit WOB
- Formation type/hardness
- Hydraulic efficiency
- Pressure differential

The ROP optimization related to the drilling operation optimization in many issues like economy, non-productive time, cost and even safety. Therefore, it is important to find the best optimizing method to use in drilling to meet drilling requirement.

The most used ROP optimization methods are:

- Maurer`s method
- Galle & Wood`s method
- Bourgoyne and Young`s method

The first and second methods depends on the WOB and RPM consideration, while the third method depends on most of the drilling parameters that make it more practical for the real time drilling optimization.

Figure (4.33) shows the parameters affecting the general ROP equation.

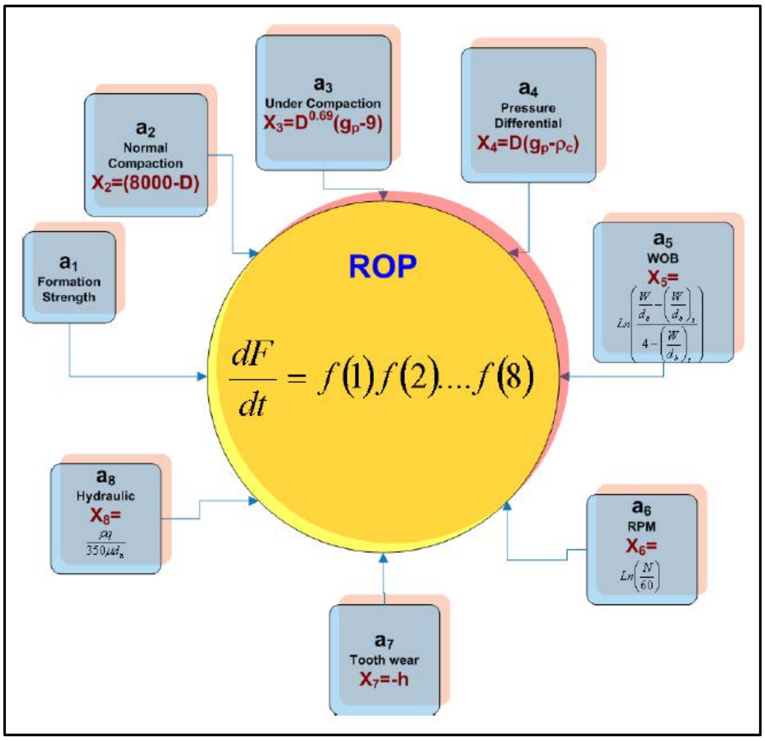


Figure 4.203: the general ROP equation [SPE 12405, 2009]

the optimization ROP used also to improve the drilling operation by identifying the ROP limitation and creating an automation system architecture using ROP optimization algorithm as figure (4.34) shows.

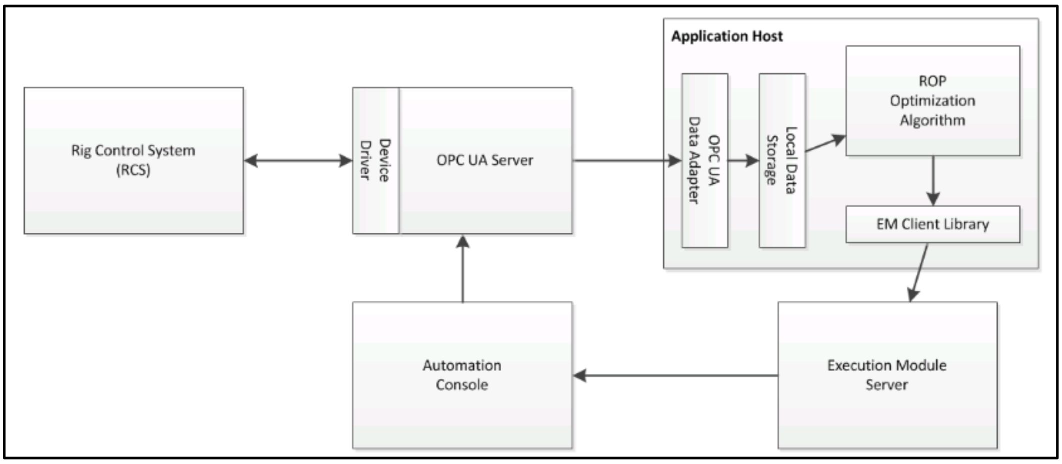


Figure 4.214: Automation system architecture. (Bertrand Peltier, 1987)

ROP limitation mentioned above has some additional details as following:

- WOB limits
  - PDC bit design
  - Buckling effect
  - The BHA design
  - Downhole tools effect on maximum WOB and depth
  - Torque and drag model to identify the WOB and the BHA design
- Torque limits & ROP limits
  - The relationship between torque limit and the bit, BHA, and drill string
  - Drill string torque profile to consider torque limits and WOB limits
  - Torque and top drive relationship.
- Surface RPM limits
  - RPM and bit design relationship
  - RPM v.s. top drive specification
  - RPM and WOB relationship
- Motor limits
  - Motor design associated with RPM and WOB
  - Rotary steerable system RSS and RPM relationship that required that RPM below the maximum speed
- Differential pressure limits
  - Relationship with motor design
  - Rig equipment limits related to differential pressure limits
- ROP limits
  - Hole cleaning as a function of ROP & RPM
  - Solid control

- Wellbore instability

The parameters effect on the ROP optimization shown in figure (4.35).

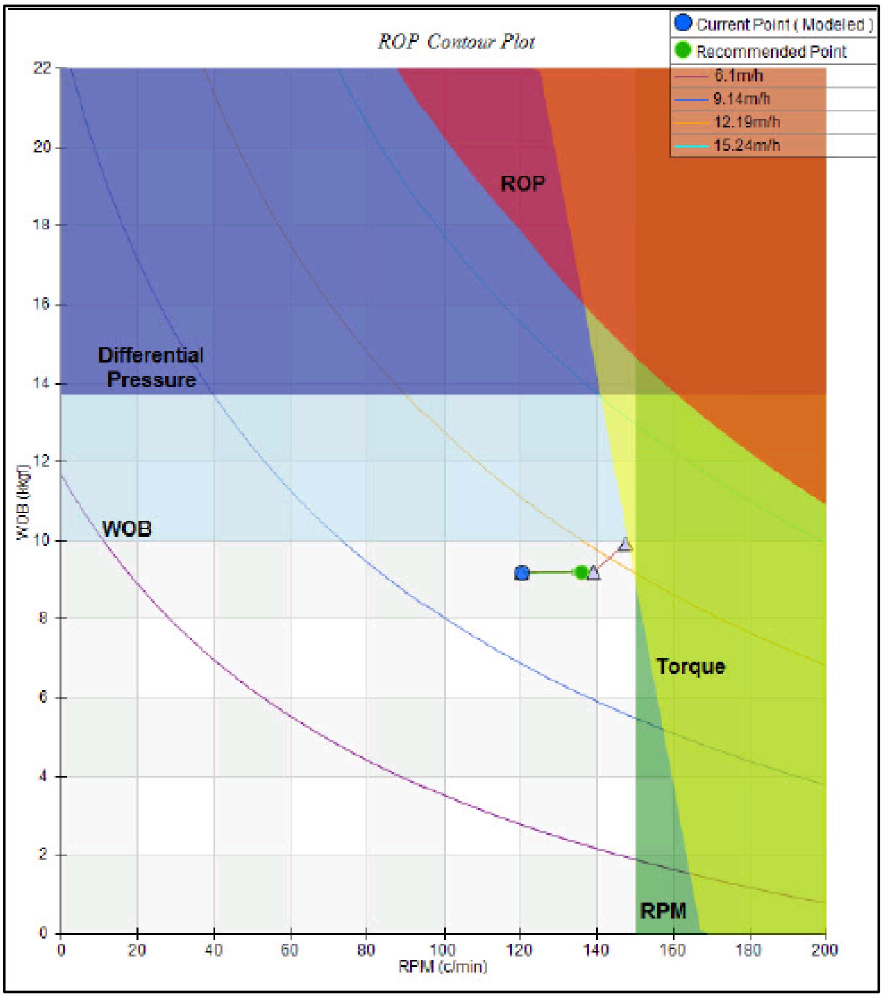


Figure 4.225: Parameter limits effect on ROP model. (Bertrand Peltier, 1987)

4.3 Model Calibration

The hydraulic model used in the drilling operations needs to calibrate with the offset wells drilled by the same way of drilling. The purpose of calibration is to compare the physical parameters used in the offset well to the current well to optimize the data input to the model. The benefits of using calibration are:

- Increase accuracy of the next model
- Develop the operator performance
- Optimize risk management
- Evaluate the physical parameters for the current well and/or for the post analysis for the next well/s
- Model advantages and disadvantages evaluation
- Optimizing the simulation data

Online calibration is one of the modern and well-known calibration method in drilling operation. Online calibration depends on surface measurement and downhole measurement PWD to calibrate the important related parameters to the hydraulic model. The relationship between the model, measurements and parameters is extremely important in online calibration to achieve the right and unique results for the parameters calibrated used in the hydraulic model. The model robustness depends on the parameters input to the model algorithm that must has unique solution and it may crashed by the multi-solution, unsatisfied and unbounded parameters. Mathematically, a unique solution exist if the number of unknowns is equal to the number of equations, and if not the result a trivial-solution. Figure (4.36) shows the use of calibration to estimate the choke pressure and compared the result with different calibration methods of the bulk modulus β.

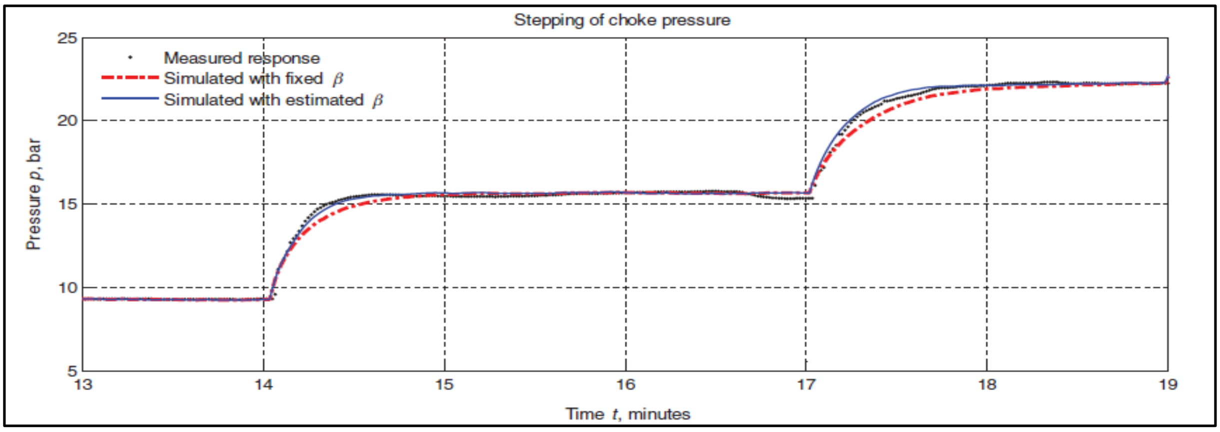


Figure 4.236: Choke pressure calibration by using different methods. (SPE/IADC 130311, 2010)

4.4 Models future work (SPE/IADC 130311, 2010)

MPD is approximately a modern method of drilling that required continuously development and optimization to meet the drilling requirements and solve drilling problems in a significant, economic, active and safely way.

There are many different models have been used in different drilling applications that associated with the well data and environment. Every model have advantages and disadvantages, so the development and future idea looking for combined models together with advantages to improve the previous models and establish new models can cover more drilling requirements.

There are different point of strength and weakness in different models. For instance, some models shows high ability in the control part relating to the choke pressure control, while another model depends on the logarithm design of control using the aspect of simple design with good tuning ability. Simplicity is a very important and central factor in the model design because of high robust and high accuracy, rather than the ease of implementation and development flexibility. This type of models are the future type of thinking and design that ensure the many issues at the same time such as:

- Simplicity,
- Flexibility,
- Sophisticated,
- Fast,
- Robust,
- Accuracy,
- Handle bad measurements, and
- reliability

There are many factors and issues involved in the drilling operation starting from the top of the rig to the bottom of the reservoir. In the future, it will be necessary to involve all or most of these factors and issues depends on the level of each factor effect on the drilling operation in general and the effect on each other that leads to effect the drilling operation.

Temperature and flow models, for instance, in the well have direct and indirect effect on the pressure regime, so involve these models in the hydraulic model will give more accuracy on the drilling performance. The big future idea is to build an architecture model consists of many models connected to each other depending on the type and level of effect on each other in a way ensures the specifications mentioned above.

The connection of drilling and automation that is almost at the third level of six of automation, which mentioned in chapter 1. The challenge of using automation and ensure the high interaction between many models at the same time seams as a big challenge today because of the difference of the automation systems used for different locations such as on the rig, in the well, and in the reservoir. An additional challenge facing the model design improvement and optimization are data treatment of the large amount of data and avoiding errors that could lead to drilling disasters. Data quality is another challenge in drilling automation reduces the development velocity especially of using advanced models for many applications parallel.

Chapter 5

Managed Pressure Drilling MPD

5.1 Introduction

5.1.1 What is Managed Pressure Drilling (MPD)

Managed pressure drilling is one of the modern drilling methods used widely in the world as a method to solve the drilling problems in the non-drillable wells such us High temperature high pressure (HTHP) wells, deep water wells, and other non-drillable wells to make them drillable. In addition to solve non-drillable wells challenges, the MPD consider as an economical method that reduce nonproductive time (NPD) or reduce it, safe operation, and high technical method.

As a definition, the International Association of Drilling Contactors (IADC) defined the managed pressure drilling as "An adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. MPD is intended to avoid continuous influx for formation fluid to the surface."

It is advisable when we want to describe the MPD operation is to compare it with the conventional drilling operation to recognize the differences and get a clear view of the MPD. The fig. (5.1) shows the drilling window between the depth and the pressure and explaining the different pressure limits in the well drilling operation.

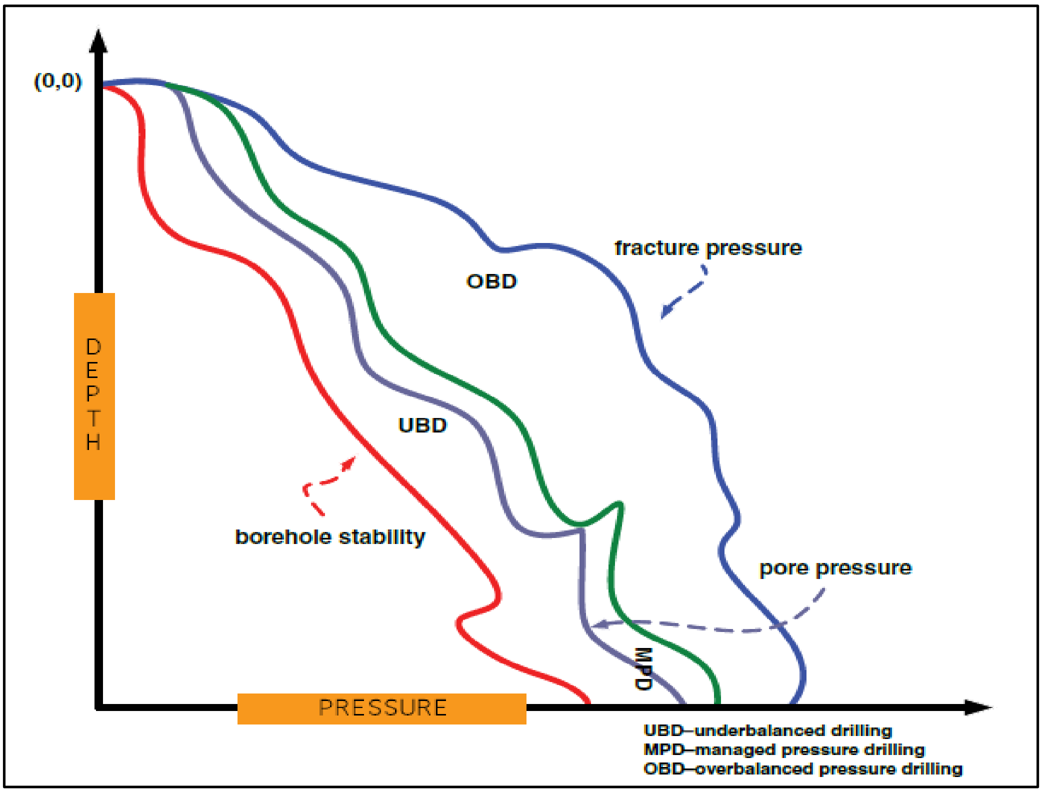


Figure 5. 2: The drilling window: Depth vs. Pressure. (Donald G. Restma, 2012)

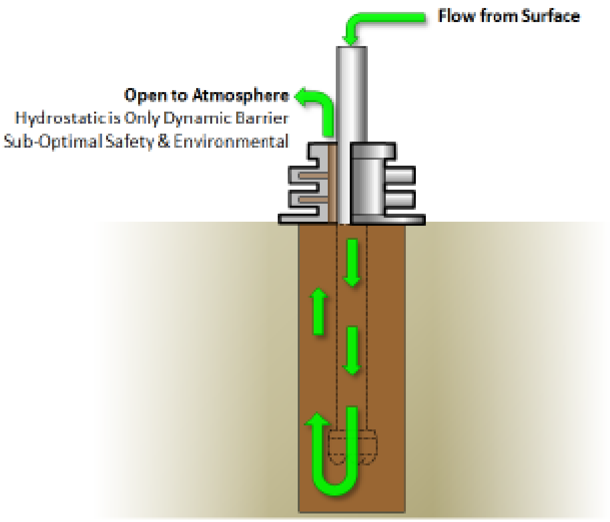


Figure 5.2: Conventional Drilling (SPE/IADC 130311, 2010)

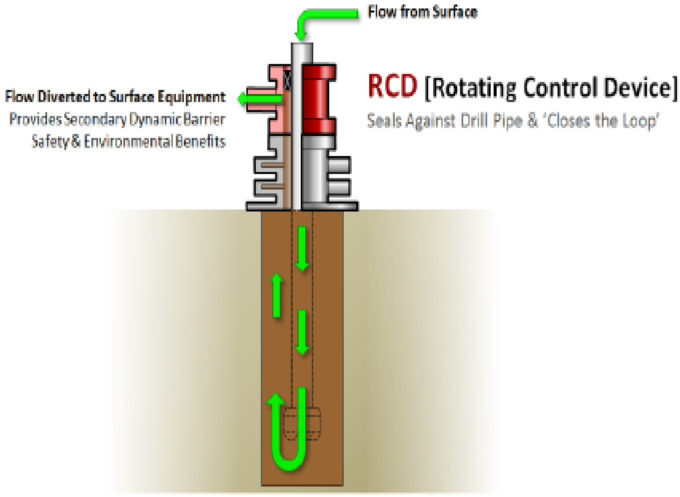


Figure 5.3: MPD. (SPE/IADC 130311, 2010)

As the fig above shows, the relationship between pressure vs. depth and the well pore pressure and fracture pressure as drilling window. The drilling operation can be describes as either open loop hydraulic operation or closed loop hydraulic operation, where the open loop representing the conventional drilling operation, and the closed loop represents the managed pressure drilling operation or the under pressure drilling operation.

The open loop hydraulic system that represents the conventional drilling operation that has the concept of controlling the bottom hole pressure (BHP) by regulating the equivalent circulating density that is a function of flow rate and fluid rheology in the dynamic drilling state. The BHP will equal to the hydrostatic pressure of the mud weight (MW) at the static state during tripping or connection. The following formulas represents the static and dynamic drilling states:

$BHP = MWgh + DPfriction$ (Dynamic Drilling)................ (1)

$BHP = MW.gh$ (Static Drilling)..................... (2)

Where g is the gravitational force and h is the well depth. The mud fluid returns to the surface at the atmosphere pressure during the conventional drilling operation.

The closed hydraulic loop keeps the drilling mud fluid in a closed loop without return it up to the surface by adding the required devices such as rotating control device and the chock to regulate the BHP pressure and keep the drilling fluid in a closed loop. To achieve the BHP controlled and approximately constant, another pressure required called backpressure add to the closed loop system to ensure the BHP controlled during the static and dynamic drilling state. The formulas 1&2 will consist the new factor that is the backpressure to the BHP as follows:

$BHP = MWgh + DPfriction + backpressure$ Dynamics drilling

$BHP = MWgh + backpressure$ Static Drilling

By regulating the chock setting and the backpressure, the BHP pressure controlled and maintained. The closed hydraulic loop system used in the drilling applications showed in fig (5.1), which are underbalanced drilling (UBD), managed pressure drilling (MPD), and the overbalanced pressure drilling (OBD).

5.1.2 MPD Categories

There are two categories of MPD as follows:

- Active MPD
- Proactive MPD

Active MPD

That category means that all equipment required activating MPD operation will be rigged up as quick as possible to compensate a conventional drilling operation that unable more to complete the drilling job because of any unforeseen drilling event relating with pressure or anything else the conventional drilling cannot deal with it.

The well plan in this situation will designed as a conventional drilling operation with an exception of equipped the rig with MPD required equipment such as RCD, chock manifold and any other needed tools to be ready for any drilling surprises happen during the operation. This category used for many years ago.

Proactive MPD

In this category, the well planned and designed from the start as a MPD application to manage the wellbore pressure profile and equipped with all the required tools to accomplish the drilling operation such as casing design, drilling fluid/mud design and any further design required.

This type of MPD, according Hannegen and Malloy (Donald G. Restma, 2012), is the effective and benefit method both for offshore and onshore to control the pressure profile throughout the exposed wellbore. The benefit of using MPD, regardless the extra planning and cost, more than using the conventional drilling method. Proactive MPD ensures active solutions for some main drilling problems to leads to provide more active pressure control, less casing numbers, and more effective mud control. Proactive MPD especially used to find practical drilling solutions for wells to optimize drilling operationally, economically and drill the drillable wells.

5.1.3 Why Managed Pressure Drilling (MPD)

The oil and gas industry had many drilling problems relating with some issues like safety, economy, and environment in some challenging wells to drill such as HTHP wells, high depth non-reachable wells, depleted reservoir wells and many other types of problems. When the oil and gas industry faced such problems, a new kind of thinking started to find the required techniques and methods to come over these problems. MPD is one of the drilling technologies and techniques that used to solve many of the drilling problems faced the industry. MPD has high flexibility and many techniques that could cover many different drilling problems. These techniques ensure the ability of reducing the industrial risk of kick producing as the most critical drilling problems, predicting the kick earlier to manage it, and reducing the kick volume. One of the most effective, useful and impressive technology in MPD is the ability to be developed for the near and far future to cover more and more drilling problems and ensure profitability of using MPD in drilling especially for the high ability developed drilling system that is automated MPD.

Automation drilling, specially automated MPD is the today and future oil and gas topic that discussed continuously to find the new techniques and technologies that may make a revolution in the oil and gas industry. The various drilling methods/techniques that the MPD have, makes MPD more efficient than the other techniques and methods to think about a full-automated system for the future.

The answer of (why managed pressure drilling?) summarized as the following:

- MPD can solve many drilling problems.
- MPD flexible because of the multi-techniques it has.
- MPD ensure effective, economical, profitable solutions.
- MPD has high future development possibilities.
- MPD is the future automation topic.

The most problems faced the drilling industry was:

- Lost circulation.
- Stuck pipe.
- Kick.
- Twist off.
- Shallow water/gas
- Flow.
- Wellbore instability.

All these problems are directly or indirectly pressure problems that leads to about 40% NPT time of the total drilling operation time, which cost a lot for the drilling industry rather than the other issues mentioned before such as environment, health, quality and so on.

5.2 Types of MPD techniques and it's applications (Toft, 2013) (Anton Cervin, 2002)

MPD has many drilling techniques depending on the drilling conditions and environment that divided into the following:

- MPD Main categories:
  - Mud Cap Drilling (MCD)
    - Pressurized Mud Cap Drilling (PMCD).
    - Controlled Mud Cup (CMC)
  - Constant Bottom Hole Pressure (CBHP).
    - Friction Management method.
    - Continuous circulating method
  - Return flow control.
  - Dual gradient drilling (DGD).
    - EC-drill. Low riser returns (LRRS)
    - Riserless dual gradient method/ Subsea Mud lift Drilling (SMD).
- MPD sub-categories
  - Continuous Circulating Concentric Casing MPD.

- Riserless MPD.
- Dual Gradient Riser Drilling.
- Deepwater Surface BOP application of MPD.
- Downhole Pumping MPD.
- Hydraulic Flow Modeling and Process Control Computers.
    - Dynamic Annular Pressure Control (DAPC).
    - Micro Flux Control (MFC).
- Secondary Annular Circulation (SAC).
- Compressible Fluid MPD.
- Wellbore- Strengthening MPD.
- Drill Thru the limits (DTTL) MPD.

Every drilling method of the mentioned above has self-conditions leads to choose a specific drilling method of them. The next section we will take a roundabout the main MPD drilling methods mentioned above. Some of the MPD sub-categories will discussed individually in this thesis depending on the related subjects taken in the thesis.

4.2.1 Mud Cup Drilling (MCD)

In Mud Cup Drilling (MCD), mud and water pumped down the wellbore and the drill pipe to prevent kicks and control loss of circulation during drilling in fractured formation with different pressure regimes.

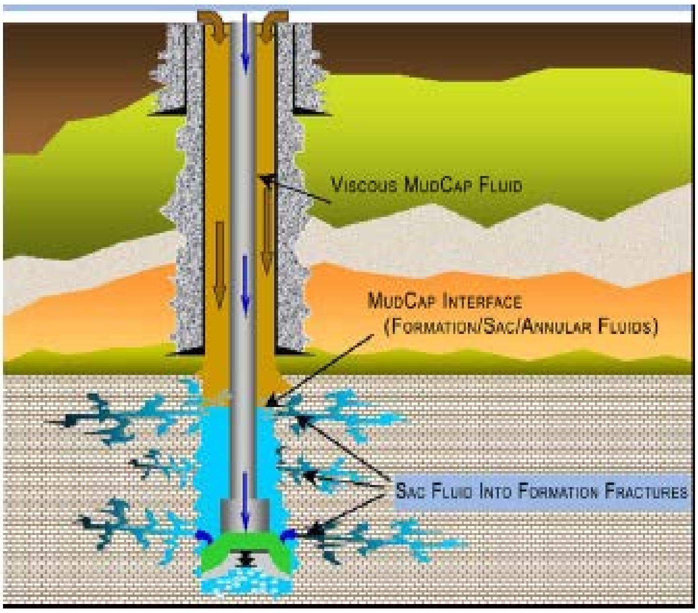


Figure 5.4: Mud Cup Drilling (MCD). (Totland, 2014)

5.2.1.1 Pressurized Mud Cup Drilling (PMCD) (Macpherson, 2014)

This method used in when the reservoir pressure condition could leads to loss of circulation such depleted reservoirs. The depleted reservoir is that one which connected to other producing wells resulting in reducing the reservoir pressure that could not anymore withstand the well pressure, that exerting by the drilling fluid, to prevent the loss of circulation in the depleted reservoir. In this drilling method, a heavy mud injected down the annulus to prevent gas influx to reach the rig floor. The gas influx happening because of the pressure differences occurs in different zones in the well because of the depleted reservoir. The depleted reservoir pressure is less than the well pressure that leads to loss of circulation to the depleted reservoir and reducing the well pressure to compensate the pressure losing in the reservoir because of loss of circulation. The pressure decreasing in the well cause a gas influx to the well in the well zone where the pore pressure is greater than well pressure and the mud cup injected down the annulus used to prevent this gas influx to reach the rig floor. This method of drilling ensure effective drilling by increase rate of penetration ROP by drilling with a light mud, additional to prevent the gas influx to reach the rig floor. This technique of drilling control the bottom hole pressure BHP and keep it constant while drilling to achieve

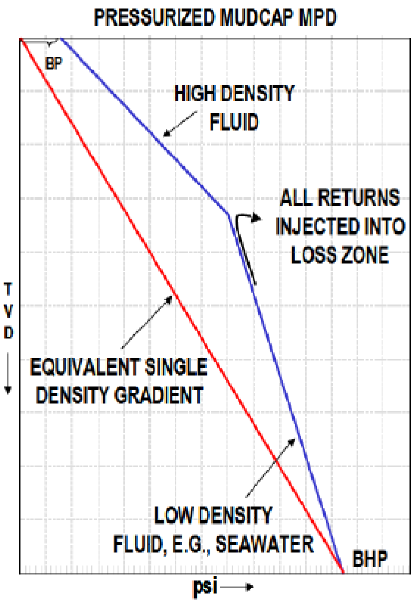


Figure 5.5: Pressure gradient profile for PMCD. (Macpherson, 2014)

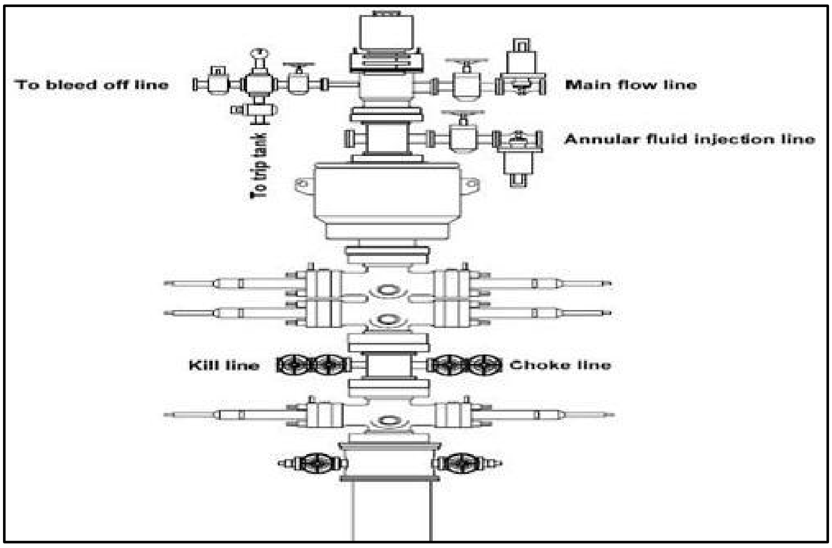


Figure 5.6: Rig up for PMCD operation (Macpherson, 2014)

5.2.1.2 Controlled Mud Cup (CMC) (Macpherson, 2014)

This method using a pump to regulate the mud level in the annulus for achieve better regulating and controlling for the bottom hole pressure (BHP). The mud pump located on the see bed as one of the subsea equipment and using an outlet joint as a connection element to the riser and from the other side, the pump connected to the mud bit to fill or return the mud from/to the riser. The system using pressure sensors to monitor the mud level in the riser and these sensors located along the riser for doing this feature. This system almost the same as the previous system (PMCD) with one different that is the mud pump.

This system has a concept of two main things:

- Recover ECD, equivalent circulating density.
- Regulate the BHP, bottom hole pressure.

The benefit of using CMC system is that it used as an open or closed system. The advantages of CMC as an open system are:

- During connection, to keep the pressure constant, there is no need to use a specific element, closure, to do that. The CMC system will have the ability by heavy mud, and sometimes fill part of the riser with gas, keep the pressure constant during the connection.

- The ability of adding a positive riser margin to the system. The riser margin will equal or less than the see water hydrostatic pressure that improving the BHP in case of riser margin disconnecting.
- Hydrocarbons management, where the riser acts as a separator for the hydrocarbons to gas, liquid, and transport the liquid out to the rig.

The CMC system acts as a close system in case of control problem such as influx by a specific procedure in a very short time as follows:

- Close the BOP
- Increase the mud level to stop influx or to make the pressure close to the annulus shut-in pressure.
- Close the surface RCD.
- Open the chock to regulate the gas pressure.
- Bled off the gas to the atmosphere.

The CMC system using a differential valve in the drill string to avoid pressure unbalance problems between the annulus and the drill pipe that leads to u-tube effect between them. Fig () shows the CMC system.

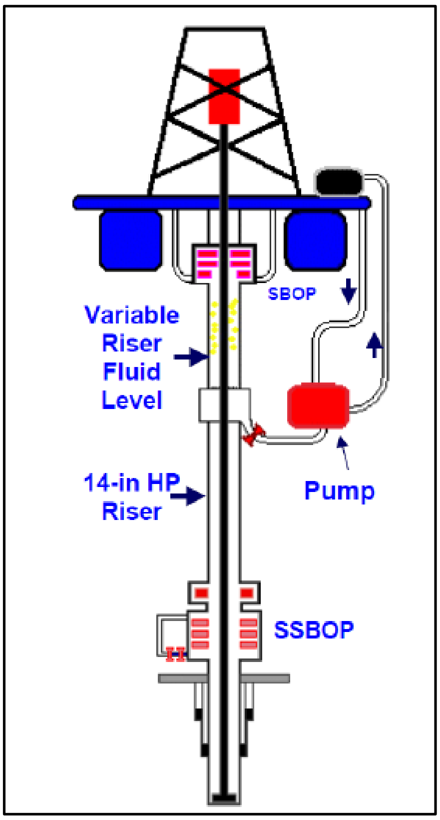


Figure 5.7: Controlled Mud Cap system (CMC). (Mæland, 2013)

5.2.2 Constant Bottom Hole Pressure (CBHP)

This system depends on the back pressure concept understanding to solve the pressure problems occurs because of the fluctuated changes in the bottom hole pressure (BHP). This pressure fluctuation caused by the change of the equivalent circulating density ECD or the annulus friction pressure (AFP) that have the same effect and caused by the same reason. The back pressure works against the AFP and the ECD to balance the bottom hole pressure BHP at the limits between the highest formation pore pressure and the weakest formation fracture pressure in the conventional drilling situations or during pipe connection that required shut-in procedure.

The CBHP system procedure following a specific technique to avoid kick or loosing of circulation. The technique depends on the balancing of many actions together, where the pump speed reduced systematically and increasing the chock closing at the same time to ensure a constant ECD pressure until the pump reach the full stop and the chock is completely closed.

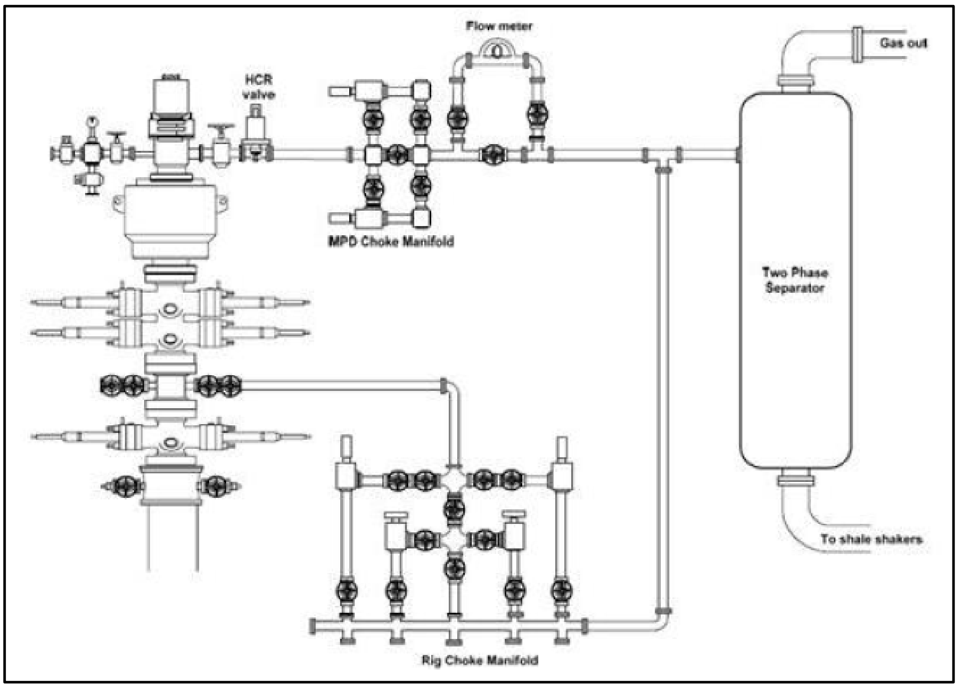


Figure 5.8: CBHP system. (Mæland, 2013)

5.2.2.1 Friction management

This method to control the bottom hole pressure in the high pressure high temperature HPHT wells and the extended reach drilling ERD wells. The HTHP wells required to keep the BHP constant as possible by regulate the circulation in the annular. While for the ERD wells have to use an annular pump to maintain the loss of circulation by regulating the back pressure in the annular.

5.2.2.2 Continuous circulation system

This method used in the wells that needs to achieve a constant friction pressure and/or in the horizontal well section to avoid cutting accumulation. A specific device used in this method pf drilling called a coupler that connecting to the drill string by let the drill string passing through the coupler. The coupler consist of two sections upper and lower section that separated by a sealing device. In case of pipe connection, the drill string sealed and the upper section provide drill fluid circulation to keep the friction pressure constant.

5.2.3 Return Flow Control (RFC)

This method of MPD drilling used as a safety control measure depending on monitoring the returns composition if it consist any kind of gases specially H_2S to scape to the atmosphere. The RFC system operated by two hydraulic valves:

- Shakers flow line valve
- Rig manifold chock flow line valve.

The valve that connected to the shaker flow line used in the conventional drilling situation where no influx problem exist, while the valve connected to the rig manifold chock used in case of any influx monitored. If any influx arise, the shaker valve closed and the gas circulated through the chock valve safely.

This system used for two situations:

- HSE reasons
- Poisoning consequences in case of:
  - Drilling with unsafety drilling fluid that result vapors on the rig.
  - Shallow gas risks.
  - Drilling in populated regions.

5.2.4 Dual gradient Drilling (DGD)

The dual gradient drilling method concept is to use to different drilling fluids in density to keep the BHP in the window between the pore pressure and the fracture pressure to avoid most of the drilling problems such kick occurring, loss of circulation, thief zone effect, drill string differential sticking, shallow gas regions effect, and achieve a stable drilling operation. Fig. (5.9) shows the DGD operation

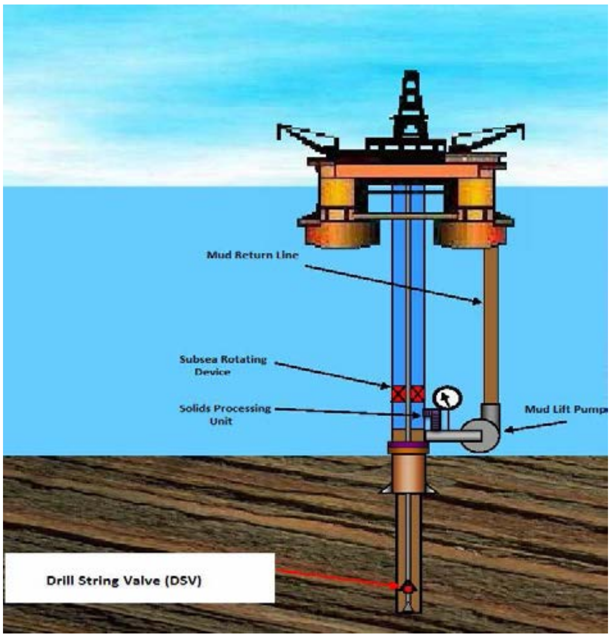


Figure 5.9: DGD operation (Singh, u.d.)

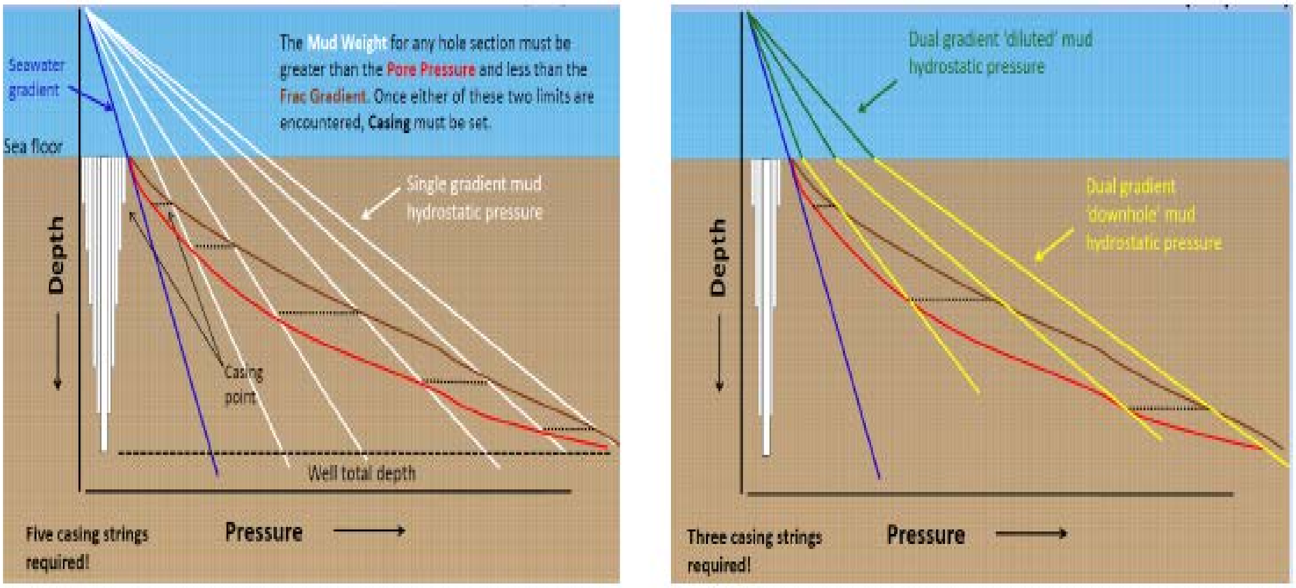
The drilling fluid density manipulated according to the well formation information and divided into two densities, lighter density for the upper part of the well, such as air, gas and seawater, and the lower part of the well using a heavier drilling fluid density depends on the drilling window at the bottom of the well.

The objective of the DGD is to achieve a BHP in the drilling window that ensure the well pressure less than the fracture pressure and over the pore pressure that might be very narrow window in many drilling cases, which called tight gradient window.

In some drilling cases such as offshore environment, special techniques required to achieve the gradient drilling window, such as running a return line from the seabed to circulate mud and cuttings. In other cases, such deep water drilling, RCD device with remote operating vehicle used. RCD to provide a circulating loop while connection and the ROV to provide the required backpressure that keeps the BHP in the planed drilling window.

The DGD detection and treatment for a kick is almost similar to the conventional drilling way, with extra monitoring devices and sensors used in the DGD than the conventional way that gives more safety and effectiveness during the drilling operation.

Fig. (5.10) shows the difference in casing number with and without using the DGD method, where using DGD method saved many casings in the well casing design.



Figur 5.10: Different number of casing between DGD & conventional drilling. (Mæland, 2013)

Fig. (5.11) shows the pressure profile for the DGD, and fig. (5.12) shows the return flow control.

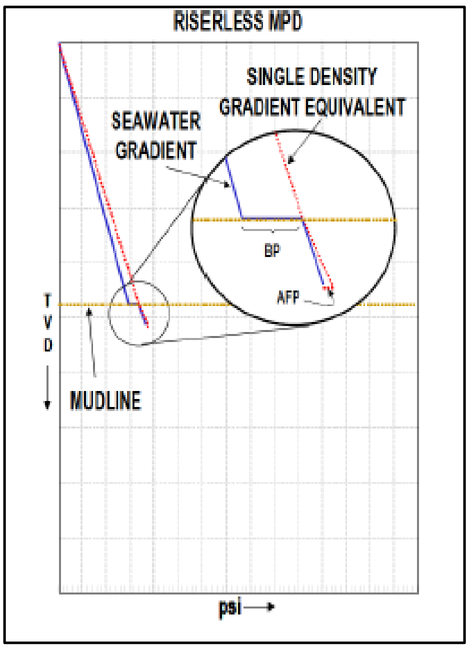


Figure 5.11: DGD pressure profile. (Rohani, 2011)

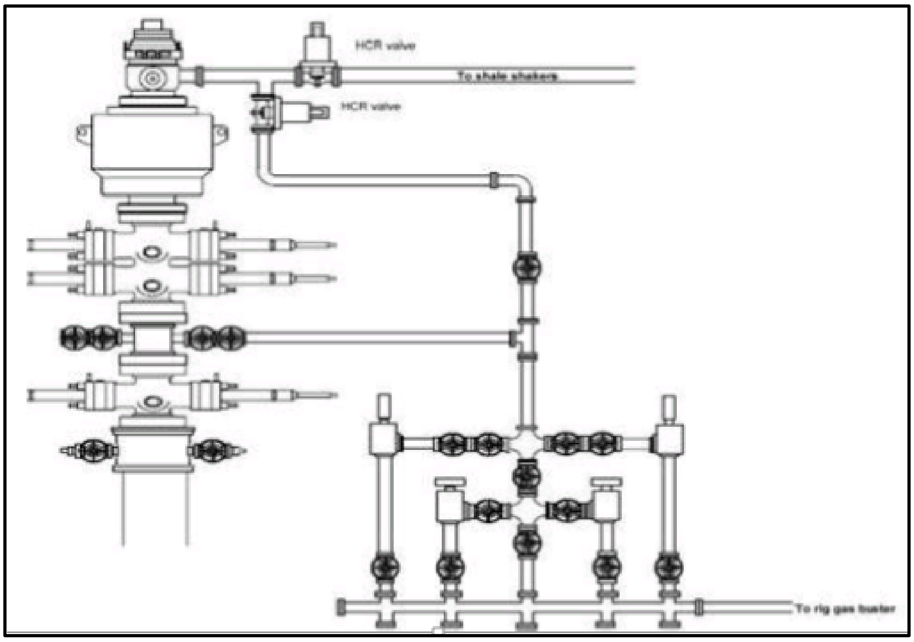


Figure 5.12: Return flow control. (Rohani, 2011)

5.3 Tools and equipment used in the MPD drilling

There are many different types of tools and equipment used in the MPD drilling associated to the different drilling method used in MPD, and the different drilling environment accompanied with the drilling operation of the related different stages of drilling.

The MPD tools and equipment used in MPD operations should ensure the following issues and the equipment related to these issues: (Enform Canada, 2011)

- Mechanical Wellbore Integrity.
  - Downhole shock and vibration
  - Contact wear.
  - Joint back off.
  - Minimize wellhead/ upper wellbore damage.
  - Stud and nut back off.
  - Excessive wellhead pressure.
  - Changing wellbore integrity.
- Surface Well Control.
  - Blowout preventer (BOP) stack.
  - Primary flow line emergency shutdown valve.
  - Rotating control device (RCD).
  - Erosion hazard management.
  - Snubbing equipment.
- Sub-surface well control.
  - Drill string.
- Surface Circulation System.
  - Piping.
  - Chocks.
  - Stand pipe bleed-off.
  - Open tank system.
  - Separator.
  - Pump lines.
- Circulating Media.
- Drill string and Drilling Rig.

The tools and equipment used in MPD are: (Tercan, 2010)

- Rotating control device (RCD) on floating rigs (wave heave)
  - External riser RCD
  - Subsea RCD
  - Internal riser RCD
- Rotating control device on fixed rig (no wave heave)
  - Passive and active annular seal design (land) model
  - Marine diverter converter RCD
  - Bell nipple insert RCD
  - IRRCH
- Non returns valve
- Choke options
  - Manual
  - Semi-automatic
  - PC controlled automatic

- Other tools used in MPD
  - Downhole deployment valve
  - Nitrogen production unit
  - ECD reduction tool
  - Real time pressure and flow rate monitoring
  - Continuous circulating valve
  - Continuous circulating system
  - Downhole air diverter
  - Multiphase separation unit
  -

5.3.1 Rotating Control Device (RCD) (Tercan, 2010) (MiSWACO, 2013)

RCD is a Safety device that used alone or with MPD to reduce the hydrocarbons movement to the surface. The RCD located on the annulus preventer additionally connected to the BOP stack to provide the safety flexibility in the BOP function.

Fig. (5.13) shows the RCD alignment.

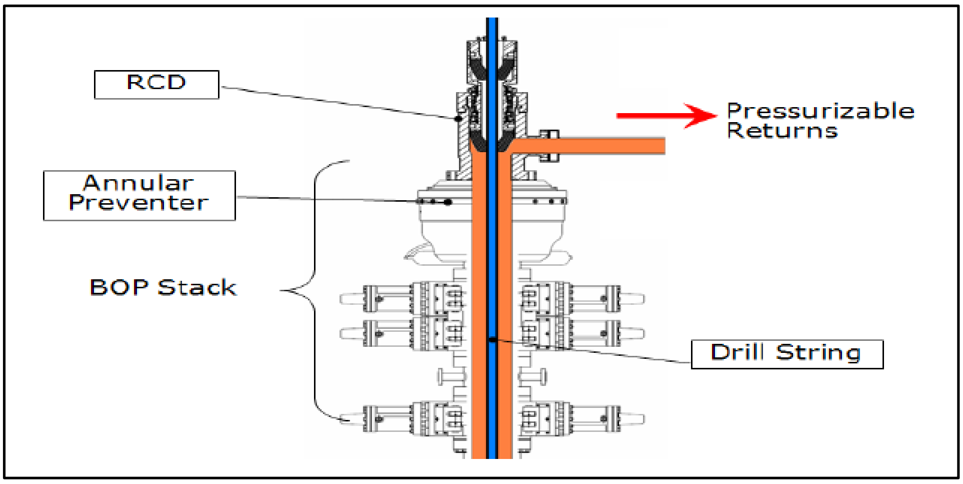


Figure 5.13: RCD Alignment. (Tercan, 2010)

5.3.2 Non-return valve (NRV)

The non-return valve used in the MPD operations as a one-way valve to prevent the fluid, with some cuts sometimes, to return to the drill pipe by the effect of the positive pressure exerting because of U-tube process. This valve support the backpressure required in the annulus to ensure pressure balance in the well during drilling.

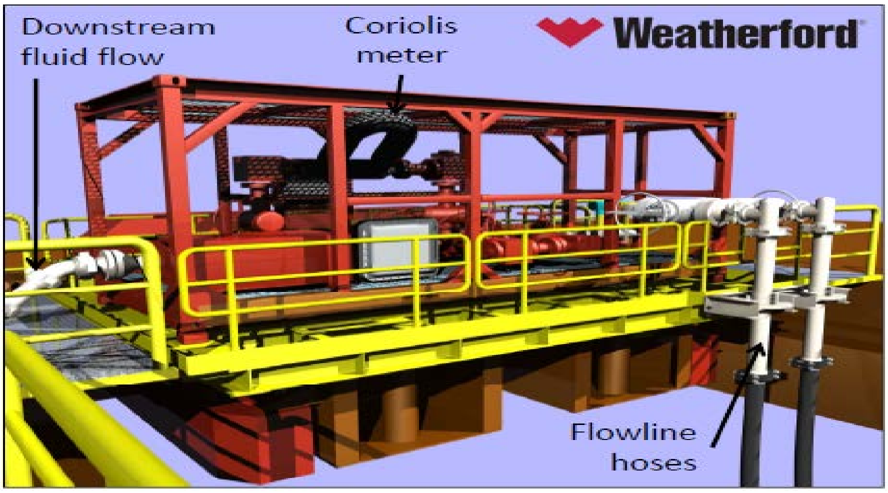
Several NRV types have different functions as follows:

- Basic piston type float
- Hydrostatic control valve (HCV)
- Inside BOP (pump-down check valve)
- Wireline retrievable non-return valve (WR_NRV)

5.3.3 MPD Choke Manifold system (Tercan, 2010) (Thomson, u.d.) (Obadina, 2013)

The chock manifold system is an important element for the MPD operation to ensure allowance of backpressure during drilling. MPD choke system is a separate system from the main manifold system that used for the routine drilling to ensure using the MPD choke manifold system just for the controlling process during MPD operations.

All the returns flow through the choke manifold that hydraulically operated to apply backpressure to the annulus. The MPD choke manifold system activated by applying the surface pressure and/ or pumping across the wellhead that required integrating between these two operations. Fig. (5.14) shows the chock manifold alignment.



F

igure 5.14: Choke manifold. (Thomson, u.d.)

5.3.3.1 Manual choke

This type of choke operated manually by an operator with aid of flow monitoring system. The choke controls the flow by changing the position of the choke manually. This system has disadvantage of expected human error that reducing the operation accuracy and increase the risk problems especially in the narrow window drilling.

5.3.3.2 Semi-automatic choke

This type of choke operated partially automatically by a semi-automatic valve using a sliding shuttle concept. The shuttle regulating the casing flow by a circular orifice depending on a set point that receiving the data measured by a hydraulic gauge.

The using of such system ensures the following:

- Stable BHP during connection
- Change of BHP according to the mud weight change.
- Continuous drilling through high pressure gas zones
- Increasing rate of penetration (ROP) optimizing
- Reducing gas-cut mud effect

5.3.3.3 PC automatic choke

This system consist of the following components:

- Mass flow meter
- Pressure sensors
- Hydraulic power unit (HPU)
- Intelligent control unit (ICU)

The system includes two chokes, main choke used continuously, and a contingency choke for urgent situations. The automatic choke system feature is to control all kinds of pressure in the well and apply the required backpressure that acts against the Annulus Friction Pressure (AFP) during drilling.

The system controlled automatically by using a programmable computer by many different programmable software used in the oil industry.

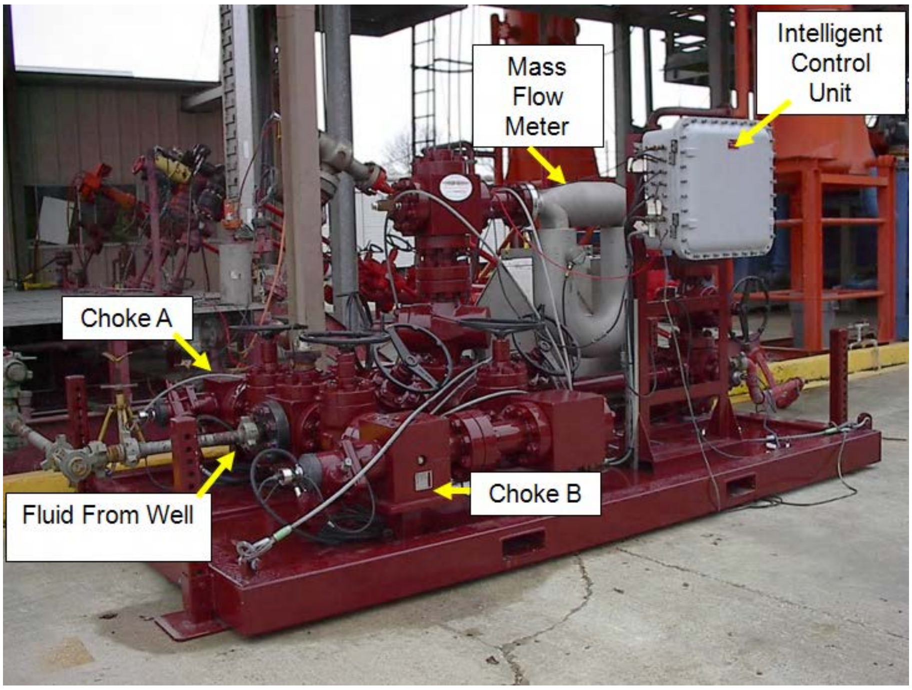


Figure 5.15: PC automated choke manifold. (Tercan, 2010)

5.3.4 Other MPD tools.

5.3.4.1 Downhole deployment valve (DDV)

This valve used at the well bottom to ensure the tripping operation successfully implemented without killing the well. This kind of technical solution ensures time saving to reduce non-productive time NPT.

There are different types and names for the downhole deployment valve that each has different technical feature than the other, as follows:

- Downhole Isolating Valve (DIV)

- Casing Isolation Valve (CIV)
- Quick Trip Valve (QTV)

The c technique of operating the Downhole Deployment Valve (DDV) depending on the pressure up and down the valve, where it open when these pressures are equal and closed in case of pressure different to prevent overpressure caused by gas or kick.

The DDV disadvantages such as it cannot used for a long time because of the rubbery seals used in the valve, casing enlargement required, pressure limitation and umbilical protecting required during cementing.

5.3.4.2 Downhole air diverter (DHAD)

The DHAD is one of MPD tools that used for diverts the pneumatic fluid from the casing to the annulus to ensure pressure requirement according to the MPD operation. The tool described as a drill pipe or collar consist of two sonic nozzle valves and the drill string may have more than DHAD to cover the needs of fluid diverting depending on the MPD goal and type.

The DHAD have several advantages relating to the pressure, well cutting removing, bit angle regulation and flow velocity.

Figure 5.16: Downhole air diverter (DHAD). (Tercan, 2010)

5.3.4.3 Multiphase separation system

Such kind of separation system necessary to cover the MPD different applications especially dual gradient drilling. The concept of such system is to provide several separation designs harmonious with the change of MPD application in a drilling operation. There two main types of separator:

- Vertical separator that mainly designed to separate gas from liquid.
- Horizontal separator that designed to separate different density liquids from each other.

The multiphase separation system might be the combination of several arrangements to meet the needs of different MPD applications.

5.3.4.4 Coriolis flowmeter

Measurement is one of the important and critical issue in MPD operations and it is playing a sensitive role in the control system procedure, so from this point of view can be imagine how important the Coriolis flowmeter as a tool of MPD.

The Coriolis flowmeter have the following specifications:

- Measurement accuracy op to 0.15%
- Measures mass flow and densities additional to flow measurement
- Typical for scullery flow measurement
- High risk erosion effect of high flow rates that should be considered
- Avoid gas/ solid ingathering.

Figure 5.17: Mass flow meter (Coriolis flowmeter). (Tercan, 2010)

5.3.4.5 ECD reduction tool (ECD-RT)

Fig (5.18) shows the component and the procedure of the ECD reduction tool.

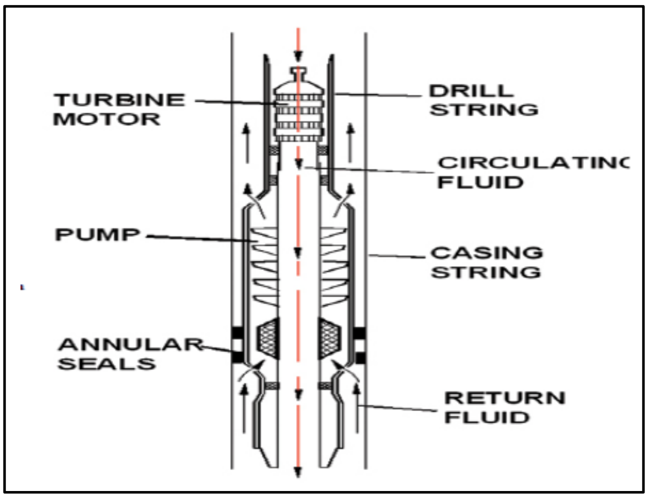


Figure 5.18: ECD reduction tool components and procedure. (Tercan, 2010)

The main feature of this tool is to compensate the backpressure implementing especially at deep well drilling. The motor in the ECD-RT tool apply an additional energy to the return fluid to provide a sudden change in the annulus pressure to reduce the effect of the equivalent circulating density ECD.

This provides a constant BHP both at static and dynamic drilling situations.

5.3.4.6 Real time pressure and flow rate monitoring system

This system is the heart of control management in the MPD applications and operations that provides the necessary data, information and measurements needed to execute, develop and control any MPD operation.

The real time pressure and flow rate monitoring system provides:

- Early kick detecting

Lost circulation detection the controlling of kick and loose circulation effecting the following drilling issues:

- Cost and economy
- safety
- wellbore stability
- formation damage
- drilling performance

This system should be controlled remotely and provide practical access for the operator with suitable and practical monitoring displays such as touch screen monitor.

5.3.4.7 Continuous circulating valve (CCV)

The main feature of this valve or device is to provide a continuous circulation for the drilling fluid to ensure a constant downhole pressure BHP during the drilling operation. This device essentially used in special wells such as high-pressure high-temperature wells (HPHT) that have depleted reservoirs, which means the need of continuous BHP control to avoid any lost circulation or gas kick problems in the narrow drilling window between pore pressure and fracture pressure. Fig. (5.19) shows the continuous circulation valve that, sometimes, called continuous circulation device (CCD).

Figure 5.19: continuous Circulation Valve (CCV). (Tercan, 2010)

5.3.4.8 Continuous circulation system (CCS)

The continuous circulation system (CCS) arrangement used in the connection operations and the HPHT wells. During connection, the continuous circulation system CCS ensure fluid circulation while the drill pipe disconnected by the CCS arrangement that consist of the following components:

- Upper pipe ram
- Lower pipe ram
- Blind ram
- Pipe guide
- Snubbing head
- Snubbing slips
- Snubbing cylinder
- Mud valve
- Lower slips

While the mechanical components making up connection the system mud continuously injected through the mud valve to ensure circulation during connection and continue drilling after connection operation finish. This process reduce the non-productive time during connection at the conventional connection process and it is more safe and practical.

The system CCS ensures stable BHP in the HPHT wells because it provide circulate the effect of temperature change by the continuous circulating.

5.4 MPD limitations and challenges (Tercan, 2010) (SPE/IADC 114484, 2008) (SPE/IADC 163546, 2013) (Wenaas, 2014)

MPD is quite modern drilling technology that may meet some difficulties relating to implementing such technology, which called limitations and challenges. Some of these challenges and limitations related to the MPD operation itself, and other related to the circumstances around the MPD operation. The limitation and challenges summarized in the following issues:

- Rig consideration: in conventional drilling operation, the rig specification almost standard, similar in the different drilling operations, and equipped almost with the same drilling equipment. When MPD technology stated to implement in the drilling technology, a new challenge raised relating to the rig design needed to meet MPD operations requirements. The other challenge is related the different MPD techniques that might be used in one rig and if the rig is designed, equipped and suitable enough to handle these techniques. Economy is an important issue related to the preparation of the required rig to be profitable or not for such operations.
- Crew training consideration: MPD technology started and developed in approximately short time that faced a challenge of preparing the drilling crew to be familiar with the new technology to ensure the effectivity and safety of the drilling operation. MPD technology comes to be more and more optimizes and developed especially when automation start to be used in the MPD operation and expected to take a wide implementation in oil and gas industry in the soon coming 5 to 10 years.
- Future challenge: the clash between the new technology and what the industry wish. The oil and gas industry still hesitate of using the new technologies that offered because of many reasons such as:

- ✓ Economy: the use of the new technology may cost the industry much of two sides, to test the new technology, and to get rid of / develop the existing rig.
- ✓ Safety: the industry not completely sure about the new technology will ensure safety and if the industry prepared enough to ensure that.
- ✓ crew aptitude

- Many MPD variations vs. chosen technology: MPD have today many applications that has the ability to solve drilling problems. Sometimes, more than one application should be used in one well. This variety make the situation complicated for the logistic preparation for the drilling operation, which make the whole operation complicated instead of simplicity expected of using the MPD applications.
- HPHT wells: HPHT wells have special specifications that make it complicated in using of the MPD technology. HPHT has a very narrow drilling window between the pore pressure and the fracture pressure that it be smaller in the depleted reservoirs. This well circumstances requires complicated MPD procedure covering the following issues:
  - ✓ Management
  - ✓ Advanced hydraulic models
  - ✓ Advanced chock system
  - ✓ Continuous circulating system (CCS)
  - ✓ Pressure control while drilling (PCWD)
  - ✓ Specific mud system
  - ✓ Formation specification

  These requirements present a challenge to use the MPD technology in the HPHT environment.

- Data limitation: MPD technology requires essentially a continuous real time data to accomplish the drilling operation successfully and any lose in the data leads to risky and serious drilling problems. This kind of problems represent a technical limitation and challenge to perform an MPD operation.
- Enhanced drilling performance: it related to the mud management to ensure good hydrostatic overbalance and required backpressure, which represent a challenge according to the mud management associated with MPD applications.
- Mitigating drilling hazards: Drilling hazards connected strongly to many drilling issues such as kick, losing mud, differential sticking, and well instability, which are completely related to the control of bottom hole pressure BHP. BHP is the essential MPD challenge to achieve the whole goal of the drilling operation.
- Deep water: Deep water individually and combined with many other issues such as HPHT, formation specification, depleted reservoir, and other issued represents a real challenge to the MPD applications that needs to be considered carefully.
- Harsh environment: environment always a challenge in both conventional drilling and MPD technology. With harsh environment, the drilling limitations and challenges increase especially that related with the required continuous real time data, extra loads of heave situations, risk management and productivity time.
- Sub-salt drilling: It is very risky to drill through salt because of the following reasons:
  - ✓ Low density of the salt than the other formation that make it unstable zone.
  - ✓ Difficult to have a model to predict the behavior of the salt during drilling.
  - ✓ When drilling through salt, the drilling window became more narrow and hard to predict the pore pressure and fracture pressure.
  - ✓ Bad seismic image through salt because of the high velocity.
  - ✓ Unpredicted kick in the salt zone

All these reasons are challenges for MPD technologies.

- Unstable wellbore: Wellbore instability is a result of unstable formation leads to increase the wellbore size larger than the Bottom hole assembly BHA that leads to some drilling problems such as stuck BHA, tripping problems and collapse. Wellbore instability results unstable BHP that challenging the MPD techniques.
- MPD+ERD (Extended reach drilling): This issue related, more or less, to the directional drilling of horizontal wells. The challenges facing such drilling method are many and the most related issues to MPD are
  - ✓ Wellbore stability that explained in the previous statement.
  - ✓ Hydraulics and hole cleaning: in ERD hole cleaning is a serious issue effects the ERD optimizing and development. For MPD, hole cleaning problem effecting the hydraulic model and the pressure regime stability that effecting the BHP as a result. This issue is a challenge for MPD as well as ERD itself.
- Low ROP: one of the main goals of using MPD is to increase drilling performance, where increasing ROP is one of the clear achievement of it. The challenge facing MPD is how to achieve well control with high productivity represented by ROP. The MPD operation is a complicated operation that may facing many drilling problems to solve that leads to decrease ROP than expected. Therefore, it is a challenge for MPD to increase ROP.
- Drilled gas (nuisance gas): drilling through gas is difficult because of the ability of natural gas to migrate from layer to another. Therefore, another drilling method used like directional drilling in different drilling angles to ensure safety drilling and ensure maximum contact area between gas and wellbore, hydraulic fracturing to ensure flow path for the gas from the source rock to the well, or both of them. Generally, drilling through natural gas required many steps and equipment rather than complicated procedures to extract gas safely and effectively. Nature of gas that migrating from layer to layer brings pressure instability to the wellbore, which is a challenge for the MPD that trying to keep the BHP constant.
- High H_2S levels: H_2S is very dangerous gas for health and environment that required a careful treatment during drilling, monitoring, specific work procedure, training requirement, protective equipment both for workers and for instrument because of the effect of H_2S to make iron-Sulphide corrosion with existing of oxygen, and other reason. Therefore, all these requirements and procedures forms a challenge and limitation for the MPD applications.
- High ECD: the main objective of MPD is to ensure a constant BHP in the well during drilling for a safety and effective results. High ECD has a direct effect on the BHP stability that the MPD tries to control it. Therefore, ECD represent a challenge to MPD.
- Ballooning / breathing formation: formation ballooning happen in the well as a result of reaction between mud and some kind of formation that shapes ballooning and effect the pressure in the well. This reaction is similar to influx reaction that gives almost the same beginning effect on pressure, but the influx pressure effects keep continue, while the ballooning effects finished after a while. Monitoring and measurements required to recognize the different effect that makes some challenge and limitation for the MPD operation.

  The following factors/ issues limits and makes some challenging for the MPD applications and their effect discussed through the above-mentioned issues.
- Equipment selection
- Procedure complicity
- Cutting settling and drilling fluid requirements
- Planning, preparation and logistics requirements
- Compatibility between conventional drilling rigs and MPD applications availability

Chapter 6

Automated MPD& development

6.1 Introduction

The automated MPD is much more than MPD because it is talking about make the drilling operation partially or fully automated to solve, more or less, most of the expected and unexpected drilling problems.

Automation gives MPD more flexibility to reach the target of drilling in the main issues that are drilling efficiency, drilling safety and economy. Many drilling problems solved with starting of using MPD in addition to gives the ability to drill the untillable wells. With automation, the MPD applications improved and optimized continuously through time.

The same drilling procedure used in MPD operations almost used in the automated MPD with adding the equipment and the models required to make the MPD operation automated. Automated MPD pass through many levels of automation as shows in figure (6.1), and the technology looking for optimization the automated MPD to reach the fully automated level. The current automated MPD has different evaluations where some pinpoint it between 3-4 and other pinpoint the automation levels between 6-8.

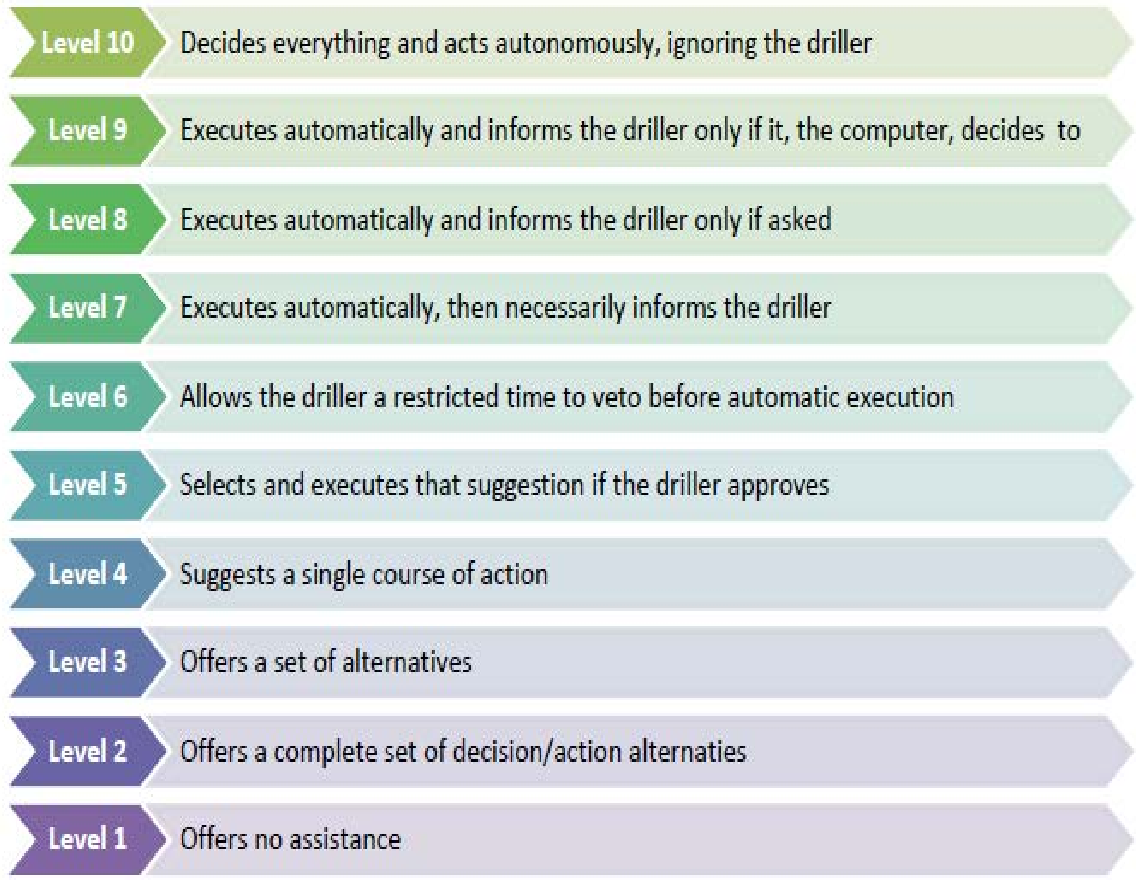


Figure 6.19: MPD automation levels (Toft, 2013)

This chapter will discuss some cases study and discuss some suggestions relating to a general view of automated MPD that expecting a step forward to optimize the automation level in MPD and drilling operation generally.

6.2 What is automated MPD

Automated MPD is a combination between automation and MPD. The MPD processes partially to increase drilling efficiency, decrease non-productive time, reduce human error, reduce cost and increase drilling performance.

Automated MPD is a downhole process automation to manage the drilling parameters, both downhole and on surface, such as pressure, effective circulating density (ECD), flow rate, rate of penetration (ROP), etc. to mitigate and eliminate drilling problems such as kick, losing of circulation, differential sticking and others.

The drilling related issues divided into two groups as following:

- Drilling
  - Equipment used in drilling associated with automation such as RCD, backpressure pump, choke, sensors, etc…
  - Control systems
  - Pre-Drilling plan and well design including simulation
  - Modeling such as geo-mechanics, hydraulic, temperature, torque & drag, drilling fluid, hole cleaning, pore pressure, etc…
  - Drilling parameters such as pressure, temperature, flow, RPM, ROP, etc…
  - Crew training
  - Safety
  - Cost
  - Variation of MPD drilling operations
  - Measure while drilling MWD and logging while drilling LWD
- Automation
  - Modeling
  - Controller design
  - Data acquisition
  - Data communication
  - Automation level
  - Multi-level design
  - Human machine interface (HMI)
  - Risk of using automation
  - PC specifications
  - Tuning of controllers
  - limitations

The aspects related to automation generally and to automated MPD in specific are:

- controller
  - PID controller
  - Feedback and feedforward controllers

- Model based controller
- Model predictive controller MPC

- Algorithm
- Tuning
- Real time modeling and Monitoring to detect and manipulate drilling problems
- Sensors

6.3 What is the level of automated MPD currently?

First automated MPD was in the Gulf of Mexico in a fractured carbonate formations well (the date didn`t mentioned) (www.offshore-mag.com, u.d.). Statoil-Hydro used automated MPD in 2007 at Kvitebjørn field successfully (Godhavn, 2009). The new automated MPD used in the McAllen and Pharr fields in south Texas at 2009 as a land drilling operation after testing the system in the university of Louisiana state (JPTonline, 2011). Camaro Nero Field in Mexico East using automated MPD to drill a very narrow pressure window that represented as un-drillable well by Schlumberger (the article written at 2013 but the operation date not clear) (SPE, 2013).

According to the history of automated MPD and the several articles and papers illustration automated MPD and its applications, the general image shows that there is no specific performance measurement in the automated MPD can be standardized, because of that the automated MPD is relating to the drilling problem itself that may vary from case to case.

The general standardization mention relating to the general explanation of the operations used in two categories:

- steady state phase
- dynamic state phase

The steady state phase defines according to the stable situation of the drilling window. While the dynamic transient phase relating to the change of the drilling window because of the change of the related parameters such as flow rate either planed or unplanned situation.

6.4 Automated MPD as a case study

MPD drilling has several drilling methods mentioned in chapter 5. Each MPD drilling method has some differences from the other relating to the drilling conditions surrounding the drilled well.

These MPD methods use different drilling tools that illustrate in section 5.3, which used for different MPD operations. Some of MPD drilling tools are common that used in most of the MPD applications, while others are specific for a specific operation.

During any MPD operation, there are a common parameters have a direct effect, action and reaction to the drilling operation such as pressure, temperature, fluid specifications, pumping rate, rate of penetration (ROP), etc. .These parameters needs to be controlled, adjust and regulate associated to the drilling environment, which related to the well status, equipment status drilling parameter reaction.

Automation in drilling operations begun on rig to automate almost all the mechanical rig operations with no need longer for human on rig to ensure safety, efficiency, and time. On rig, activities are almost repeated and can be called in another word, static that required a static automation system to control the repeatedly activities. But, when we talking about MPD, so it is a completely another story, which can be called a dynamic automation control system that required a lot of assumptions, modeling, simulation, innovation, performance measurements, and so on.

MPD defines as a complex operation compared to the conventional drilling and it require high technical skills of the operator to operate an MPD operation. Human error is a vital issue in MPD operations that led to find more robust, effective and safe method to control an MPD operation. As a development of operation control system used in MPD operation, automation was the most reliable and effective option. Chapter 2, 3 & 4 showed a view of automation in general and drilling automation. The combination of drilling and automation pass through many levels towards increasing automation level in drilling and especially for MPD.

The question coming is if the automation in drilling is a control system or a process system. The answer it will be hard unless we analyze the automation levels used in MPD, but generally, automations definition varies according to the level of automation used in MPD. The low level of automation defined as a control system to control an operation or automate a control system in an operation. While, the high level of automation considered as a process automation system that we can call it automated MPD.

There are several issues need to be discussed relating to automated MPD to analyze the current automated MPD and discuss a future visualization about automated MPD as a higher level of automation could be improved and optimized to be full automated.

The current automated MPD focusing on one or more than one parameter to control through automation as a main parameter and the other parameters related to that parameter. For instance, the Constant Bottom Hole Pressure CBHP method focus on the bottom hole pressure to keep it constant during the drilling operation, and any other parameter may effected this condition will be regulated to this drilling condition.

Automated MPD using several models associated with the drilling method used to reach the drilling target. Models used in automated MPD such as hydraulic model, thermal model, torque and drag model any many other models that mentioned in chapter 4. Figure (4.1) gives a general image about the model concept that depending on four aspects, assessment, action, acquisition, and analysis.

A fully automated MPD did not reached yet but it is in the researching phase because of the high number of parameters relating to both MPD and automation that need to analyze, simulate and test before using them in an actual drilling operation. These parameters effecting the drilling operation, the automation performance and effecting each other in a way affecting the completely automated MPD operation.

Automated MPD general concept is to control the downhole pressure during drilling by controlling and regulating the related parameters such as mud density, flow rate and so on. All related parameters automated by create a model for each parameter like flow model to analyze the flow regime during drilling and define the mathematical model suitable for this flow regime. Depending on the model, the automation program/function can be build up and choosing the suitable control system with a suitable controller associated with the model condition.

6.4.1 Case studies of automated MPD (Toft, 2013) (SPE, 2013) (JPTonline, 2011)

Case study 1:

Automated MPD using model based process control on Stafjord

This case adopted model based process control to build up the automation system with using of MPD. This automated MPD depend on the drilling process as following:

- Preparing the pre-design of the drilling operation
- Define the related drilling parameters
- Define drilling tools associated to drilling automation tolls
- Define the physical wellbore models
    - Mechanical model
    - Hydraulic model
    - Temperature model
    - Torque and drag model
    - Hole cleaning model
    - Pore pressure model
    - ROP model
- Define input data
    - Real-time measurement data
    - System configuration data
- Automation related requirements
    - System architecture
    - Functions
        - Interaction with driller
        - Data validation
        - Operational limits
        - Downhole pressure limits
        - Flow rate limits
        - Hook load limits
        - Torque and drag limits
        - + + +
    - Configuration data requirements
        - Rig editor
        - Wellbore architecture editor
        - Planned and current trajectory editors
        - Geo-pressure editor
        - Geo-thermal editor
        - Drill string editor
        - Drilling fluid editor
    - Communications specifications
    - Risk management
    - Performance measurements

The structure of this automated MPD related to using automated MPD by Statoil at Statfjord in the North Sea. The main aspect analyzed in this field is the quality of planning and design data.

At this field used the model process control system that depending on the safety factors/elements to control drilling operation by implementing the wellbore models to ensure drilling within formation and drilling tools limits.

Model Process control system based both on the static and dynamic state of the wellbore models with aid of real time measurements and advanced simulators to detect drilling problems early to take action mitigating or eliminating these problems before it becomes serious uncontrolled problems.

The level of automation in this operation based on that the automation control system will selects and execute that suggestion if the driller approved, which is the level 5 according to automation levels showed in fig (6.1). Automated MPD includes automate several tasks and the driller role is to monitor the drilling parameter to make sure that it is within the limits.

Several models used to ensure the automation drilling operation executed in the safeguarded mode and safety triggers with continuous prediction of the state of wellbore by calibrated the models with measurements. Mechanical model used to ensure the drillstring stand during drilling base on the loaded affecting on the drillstring by using the mathematical equations in torque and drag calculations that using in advance finite element method (FIM) for these calculations as two situations, soft string model and stiff string model. This model require a real time measurement for control. Figure () shows torque value during the drilling operation.

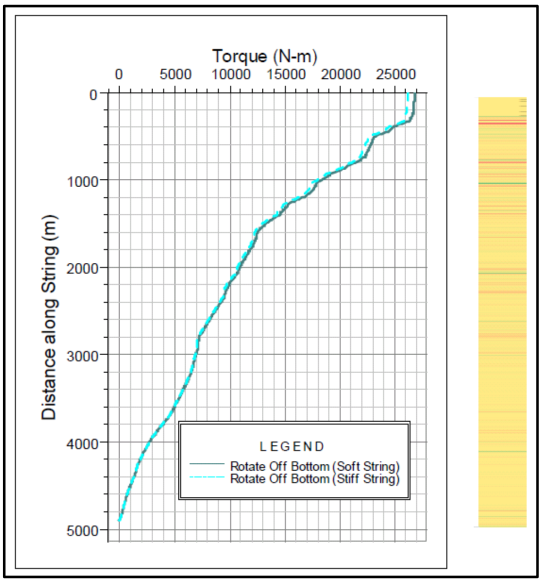


Figure 6. 20: Torque calculation by the mechanical model. (Toft, 2013)

A hydraulic model used to control pressure at any position in the annulus even if there is pressure measurement tools such measurement while drilling (MWD) because the model maintaining the pressure in case of be out of the limits. Rheology model also used to predict the share stress and share rate for the drilling fluid during drilling as necessary parameters used in the hydraulic model. The different types of hydraulic models used in this field illustrated in chapter 4.

A Temperature model used to predict the temperature along the well as a function of heat convection during drilling and heat diffusion by the formation. These two heat transfer methods effected by many factors during drilling such as density, cement slurry, formation type, rheology and drilling equipment.

The main model controlling the drilling operation is the hydraulic model to control the bottom hole pressure (BHP) and all the other models connected to the hydraulic model including pore pressure model, hole cleaning model and ROP model.

The input data to the model divided into predrilling input data and during drilling input data. The predrilling input data could be calculated data, data form a neighbor well, or predicted data based on simulating. During drilling data is measured data by the different measurement tools used during drilling. These data requires a real time calibration to ensure accuracy of the data input to the models and the model accuracy as well. Figure (6.3) shows calibration effect on Hook load modeling results

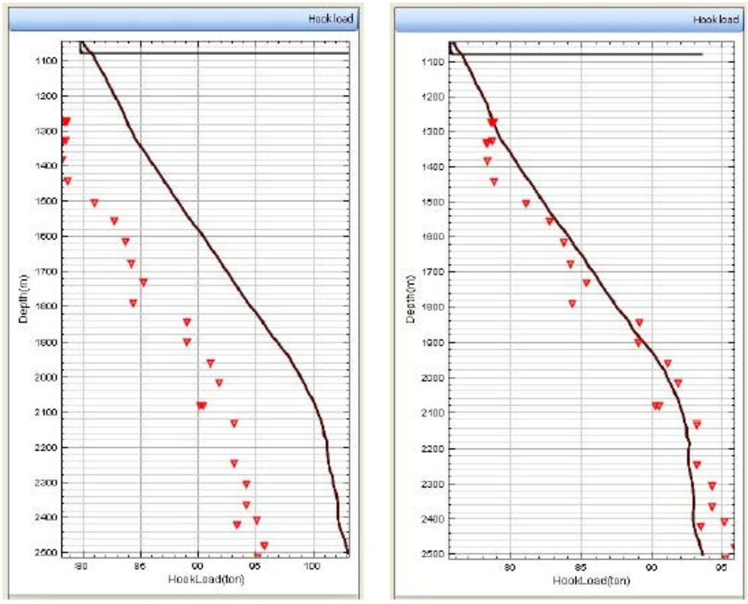


Figure 6. 21: Calibration effect on Hook load modeling results. (Toft, 2013)

The input data required to be high accuracy and in demand when needs to ensure updating requirements of the automation models. Figures (6.4) & (6.5) show the different of drilling data used in a conventional drilling operation and automated drilling operation.

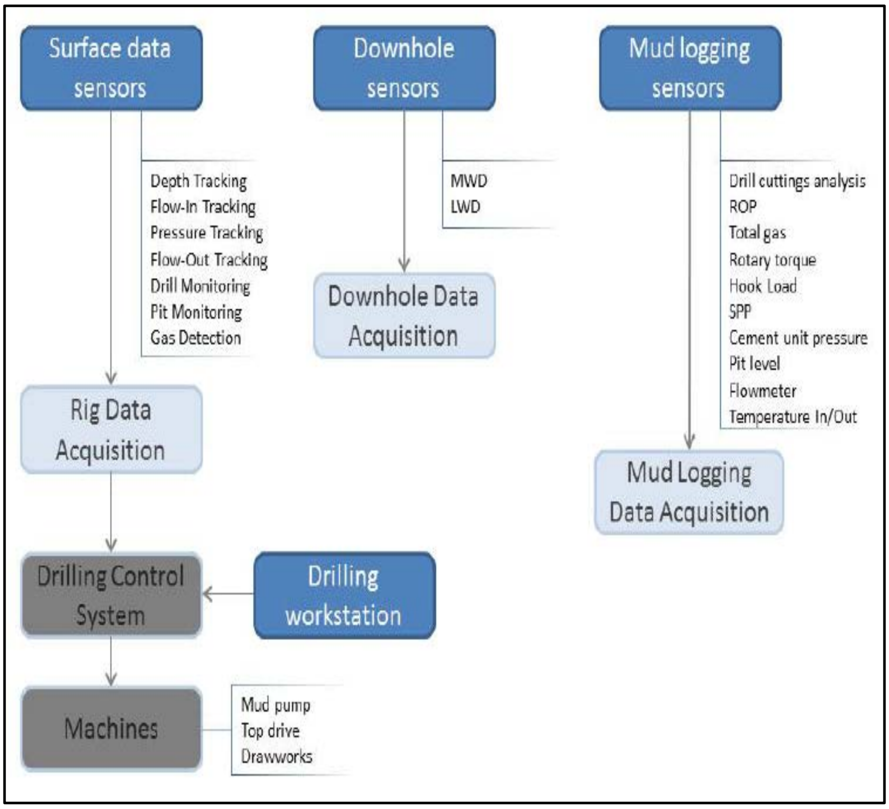


Figure 6. 22: Conventional drilling data distribution (Toft, 2013)

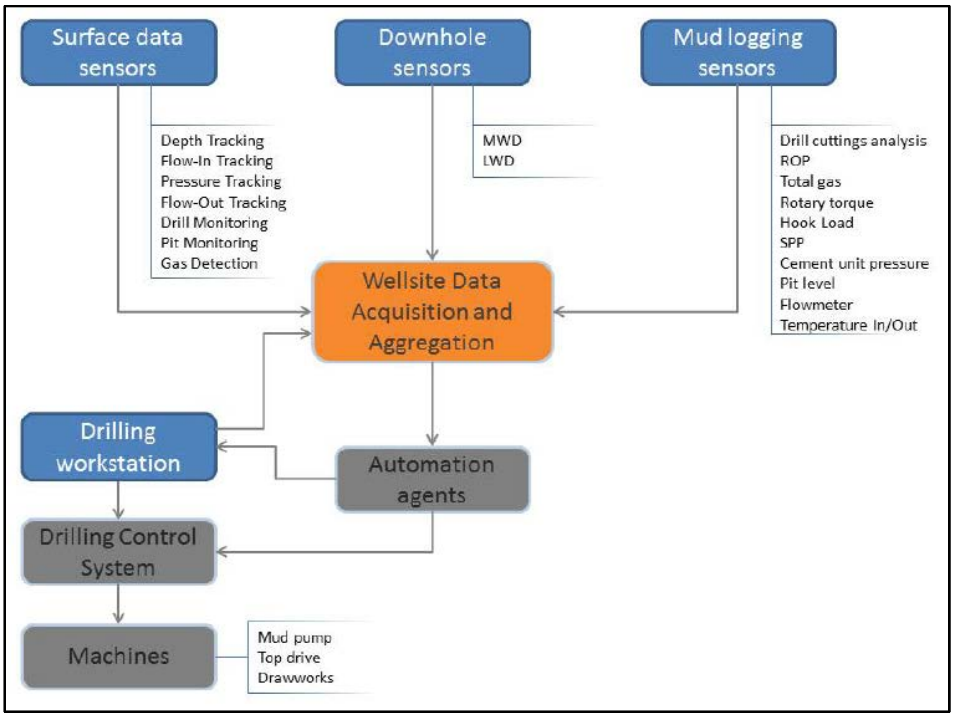


Figure 6. 23: Automation drilling data distribution (Toft, 2013)

A system configuration data required in the automated MPD that configure the drilling parameters before and during the drilling operation. The parameters configured showed in figure (6.6).

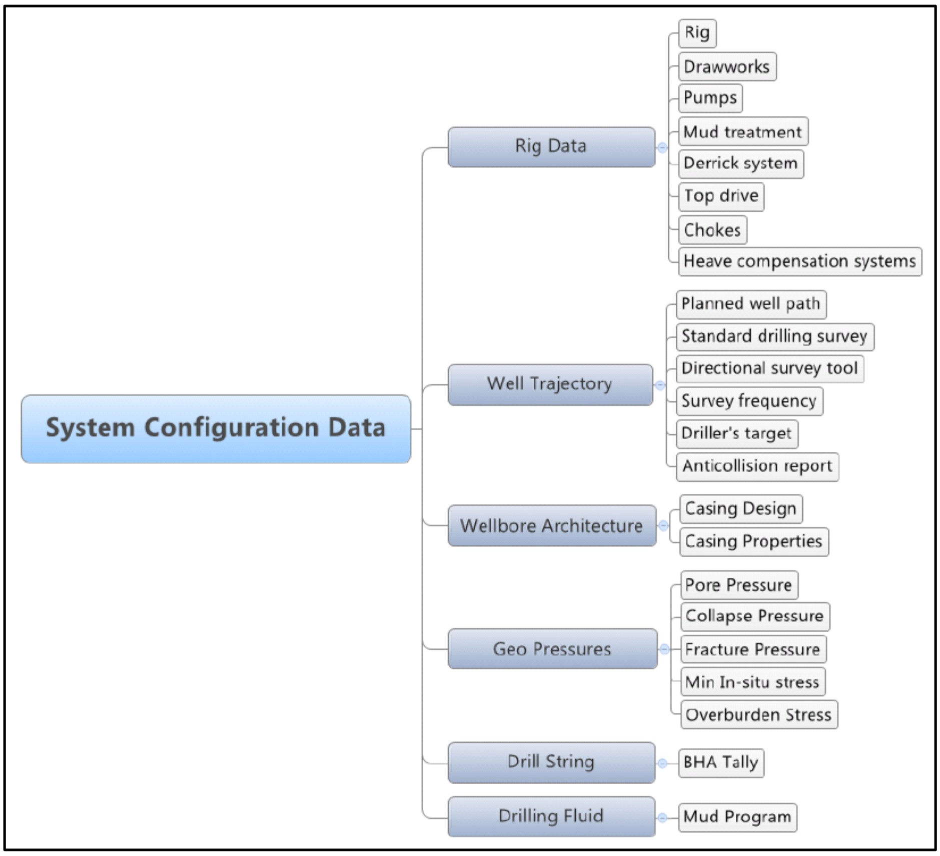


Figure 6. 24: Configuration data system (Toft, 2013)

Rig data is one of the important input data that indicating the pumping operation and the drilling tools movement to define the limits required for the automation models. Well trajectory data, geo-pressure data, geothermal gradient data, drill string data and drilling fluid data required as input data relating to model design. Figure (6.7) shows the geo-pressure gradient of the well at Statfjord.

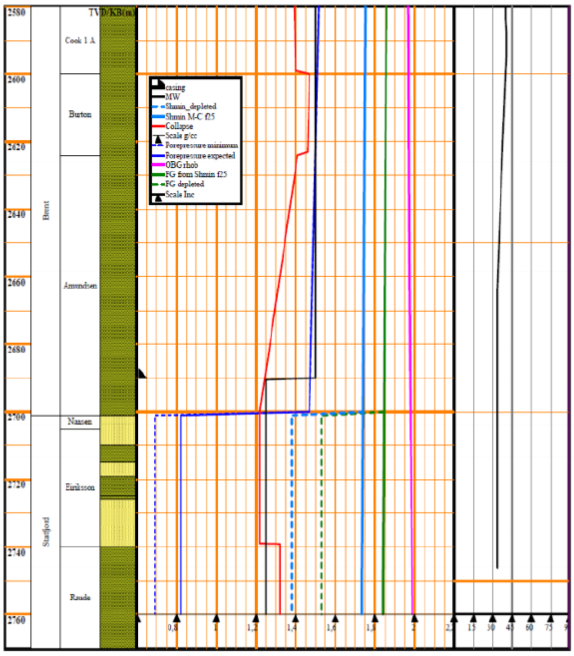


Figure 6. 25: Geo-pressure gradient of the well in Statfjord (Toft, 2013)

The system process control in automated MPD at Statfjord should cover some important issues relating to risks and challenges lists by Thorogood (2010), like:

- System flexibility to additional applications
- System ability to deal with unwanted sequences.
- Limited Bandwidth for data transmission.
- Model ability to perform calculations even for pore and limited data and ensure accuracy of results.
- Heavy equipment response to change must be slower than the system speed of change the set point.

The system architecture based on the following items

- Programmable logic controllers (PID) as shown in figure (6.8):
- Calculation modules
- Machine control server
- Sensors

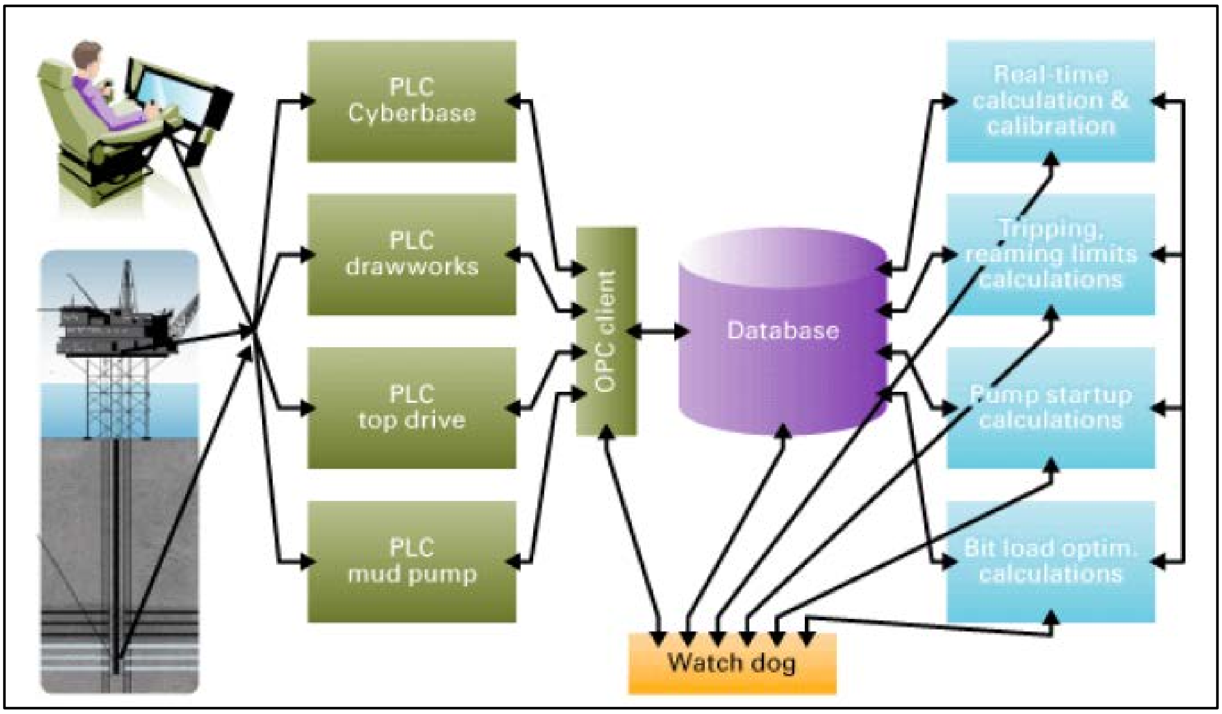


Figure 6. 26: The automation system architecture. (Toft, 2013)

The PID controllers control the drilling operation parameters depends on the sensors data, while the machine control server ensure the communication between the PID controllers and the calculating modules to keep the sensors data continuously updated for modules calculations.

There are some operational limits in this field such as downhole pressure limits, flow rate limits, Hook load limits and torque limits. These limits have to take them in consideration in the automations system design and especially in the model design.

Drilling data management in this field depended on many sources collected manually and gathered into a document called Activity program and detailed operational procedure (DOP).

The activity program based on regulations established by government, which represented by NORSOK D-010 that it consist generally of general information, HSE and operational risks, geology, activity, and organization. Additional specific information may the activity program include such as well design, mud program and so on.

The DOP consists of the suggested operational limits of the drilling operation, which is mean that the DOP have to be ready at least one day before the operation.

Another type of data id called daily drilling report (DBR) that reporting all the daily drilling activities data.

The system have been evaluated both for the stage before and after the operation. The data evaluation for each aspect in the drilling operation is central and essential for the whole system because of the dependency of the system upon configuration and acquisition data management.

Case study 2 (World Oil, 2014)

The automated MPD case in East Mexico in Camaronero field

The automated MPD case in East Mexico in Camaronero field, which had a very narrow drilling window because a previous failed drilling trial led to influx from water zone and loss of circulation during drilling. The automated MPD was a solution to drill an impossible well to drill because of the very narrow pressure window. The reason of this very narrow pressure window was a human error of a wrong decision made in a cross-flow scenario.

The automated MPD strategy was as followed:

- Using a flow model in the planning phase to determine the input data to the drilling program
- Using Constant Bottom Hole Pressure (CBHP) method as MPD method.
- Using static low mud density
- Using backpressure pump (BPP) to balance the downhole pressure by adding pressure to the annulus
- Performing controlled formation pressure test during drilling to measure the pressure window continuously.
- Performing a hydraulic simulation depends on the following parameters:
  - Wellbore geometry
  - Trajectory
  - Bottom-hole assembly (BHA)
  - Drill string components
  - Fluid properties
  - Drilling parameters
- Adjust flow rate to ensure hole cleaning
- Using oil-based mud (OBM) as a drilling fluid to ensure:
  - Minimum hole cleaning requirements
  - Minimize formation damage
  - Minimize frictional losses in the annular section
- Include rheology factor in the design consideration to:
  - Minimize hole cleaning conditions
  - Ensure bottom hole limits
  - Optimize strategies for connections and tripping
- Detecting kicks and ballooning effect

Figure (6.2) shows the MPD flow diagram used in this drilling operation. Figure (6.3) shows the drilling pressure window. The result of using automated MPD was extremely sufficient using the constant bottom hole pressure (CBHP), where gives the following results:

- Reducing losses of fluid
- Solve the cross-flow environment issue by increasing the mud weight
- Reduce well instability by about 30%
- Allow tripping with mitigating losses and influx possibility
- Provide trust in the automation drilling through MPD
- Reach the production zone safely

These results show the effeciency of the automated MPD method used in this well and how much confident was automation drilling as a last solution for the impossible driling operation. This results rising the trust level of automation by the oil and gas industry and mitigate hesitating feelings to impliment automated MPD.

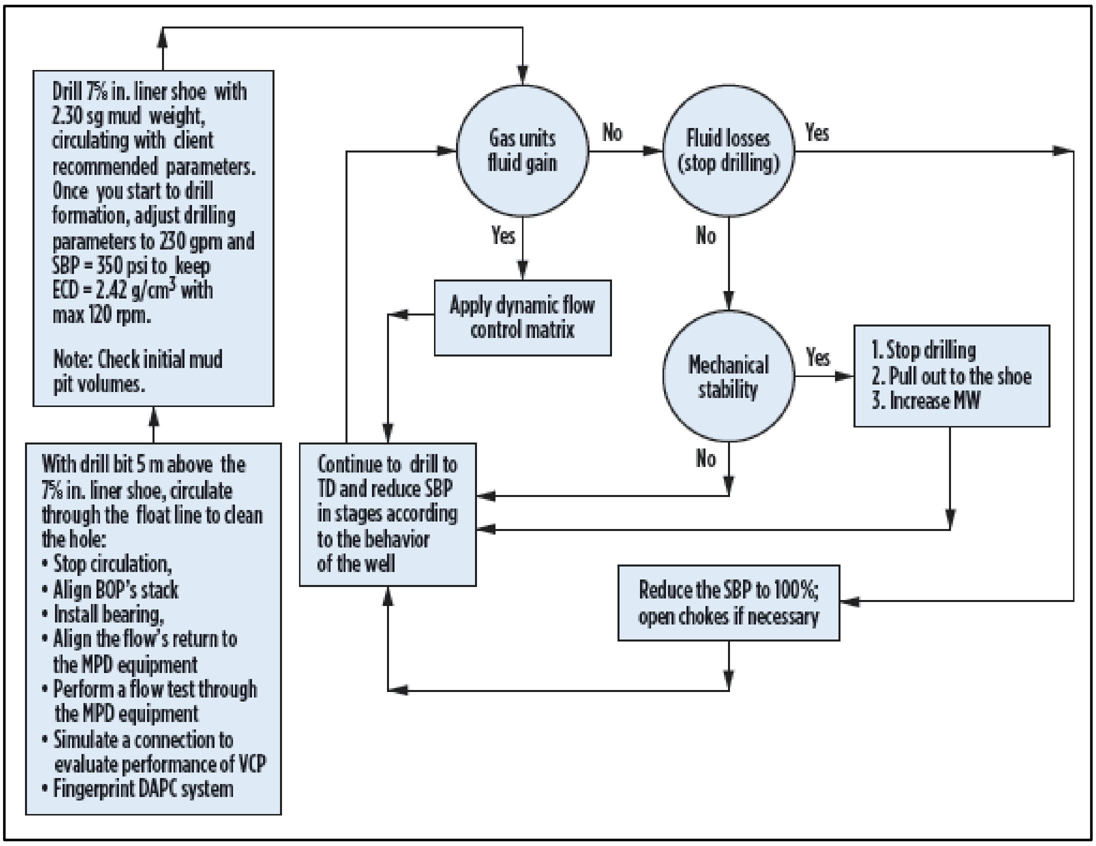
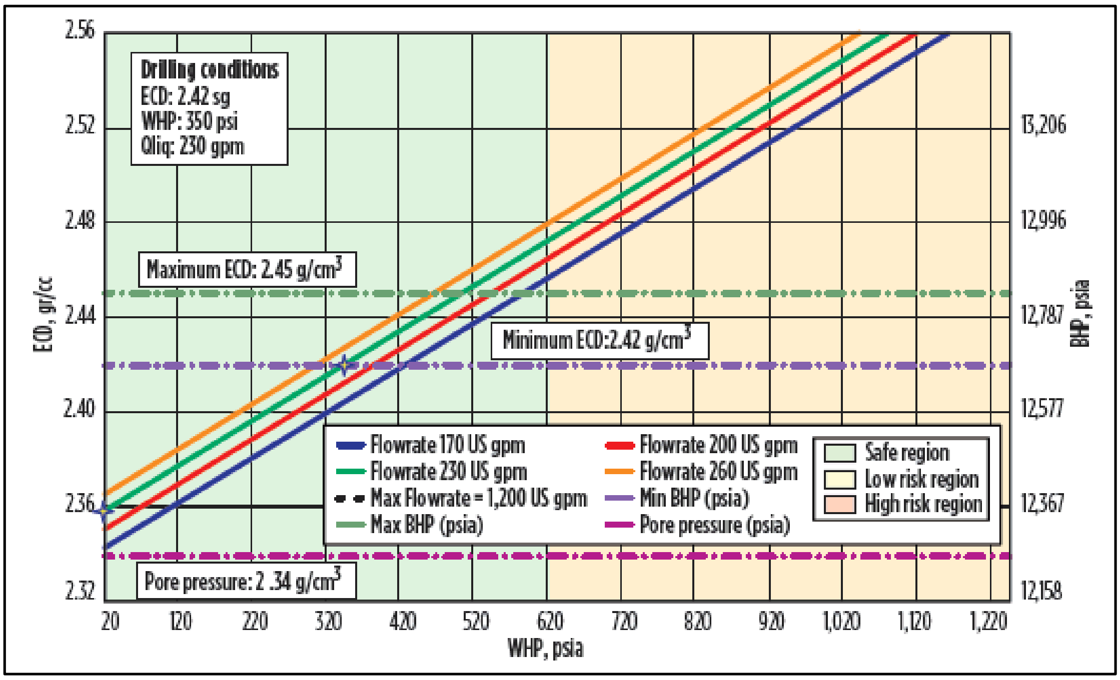


Figure 6.27: MPD flow diagram (World OIl, 2014)



6. 28: Drilling pressure operating window. (World OIl, 2014)

Case study 3

Automated MPD case in the McAllen and Pharr fields

The third automated MPD case was in the McAllen and Pharr fields that predrilled and faced loss circulation because of depleted reservoir by about 5000 psi and high permeability formation.

Automate MPD method have been used later in both fields with some modifications in the automated MPD system used in the Gulf of Mexico fields that was consist of:

- Choke manifold
- Backpressure pump BPP
- Coriolis flowmeter
- Automated pressure-relief choke
- High-pressure rotating control device RCD

These tools collected in a self-contained choke manifold to meet the onshore MPD operation requirements. The manifold examined in the University of Louisiana that led to remove some hardware to reduce the size and weight of the manifold to meet the lifting requirements.

Real-time hydraulic model used to ensure constant BHP in the annulus associating to some drilling parameters and to determine ECD in the well during drilling. The first well used automated MPD to manage the BHP during drilling and using BPP during connection, while the second well used to control the ECD at a constant BHP and during connection used trapping BPP. The model required tuning and simulation for training purposes.

Case study 4 (SPE, IADC, 2014)

The case of automated MPD in Canada

This case of automated MPD in Canada that used two different automation levels according to the automation levels mentioned in chapter 2 section 2.7. Where applied level 3 in the Deep Basin of west central Alberta in Wilrich wells and level 7 of automated MPD in the Falher F in the Cutbank area of west Alberta.

In these two cases the level of automation was different because the second case couldn`t reach the True Depth (TD) of the well by a low-level automation because of the very narrow drilling pressure window in this case. Figure (6.6) shows level (3) of automated MPD.

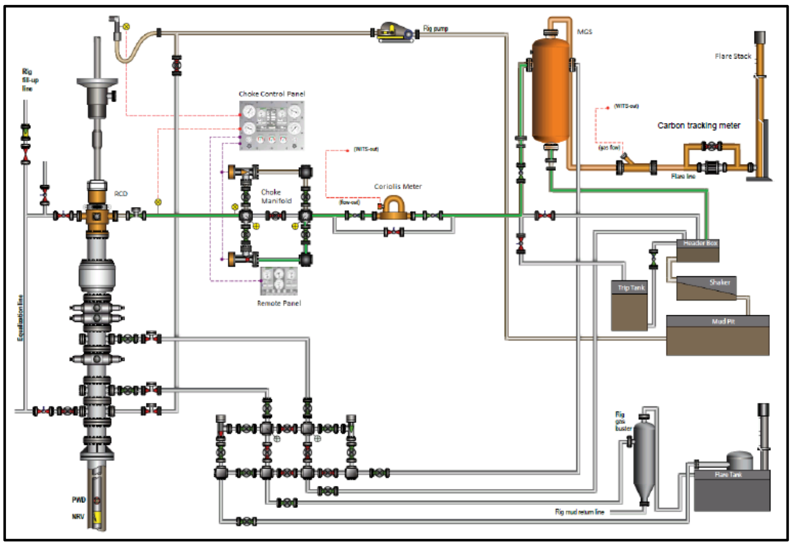
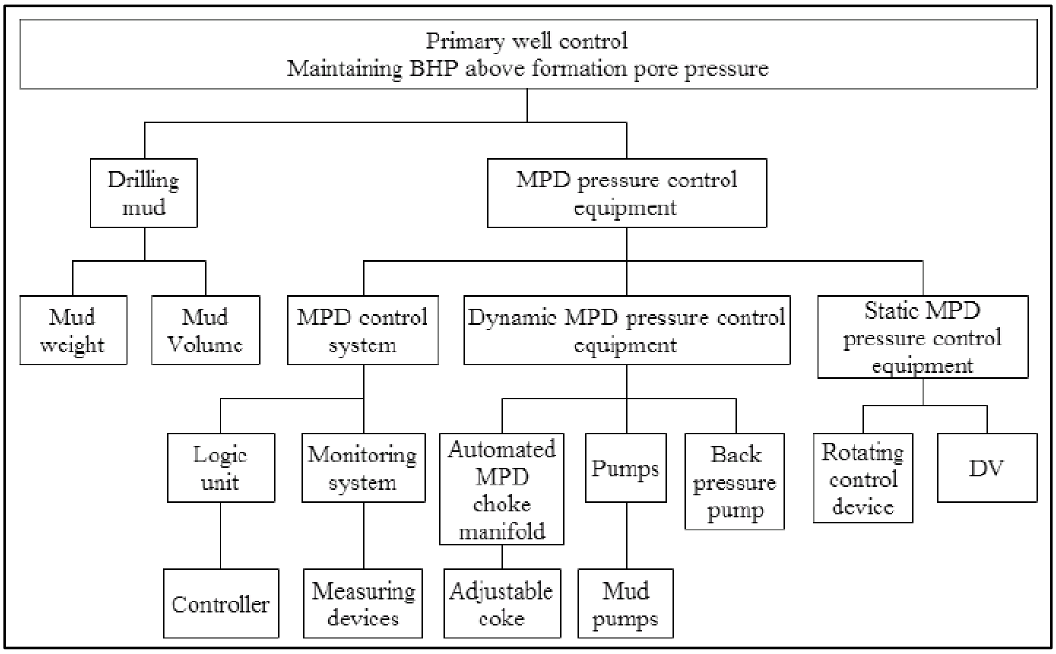


Figure 6. 29: Level 3 of automated MPD. (SPE, IADC, 2014)

6.6 The general structure of automated MPD

Figure (6.4) shows a general structure of an automated MPD operation to maintain the BHP above the formation pore pressure.



6. 30: Automated MPD structure. (SPE, 2013)

The steps sequence taken in an automated MPD operation are:

- Planning
- Tooling
- Modeling
- processing
- Measurement
- Analyzing and simulation
- Trust

6.6.1 Planning

This phase like a study or predesign of the well by collecting all the information and data needed about the well like seismic data, reservoir type, drilling program, mud requirements, well size, and many other parameters related to the automated MPD operation. This stage consider as a preparing stage before the drilling operation to cover and meet all the operation requirements.

The automated MPD is a complicated operation that required high planning skills, robust planning, dynamic and flexible in some cases, and practical planning as well to ensure safety, economy and efficiency.

The automated MPD has two main aspects relating to planning, which are automation and MPD. These aspects can be planed individually or combined depends on the process the operation going throw. Some process required an individual planning for automation and MPD separated, and another process required a combined planning for both automation and MPD. For instance if the drilling operation works without any unwanted events such influx or loss circulation, so the planning is related, more or less, to the MPD operation and the automation role will be measurement, analysis and monitoring. While if the process has unwanted drilling problem requires an automation interface, so the planning following the combination between automation and MPD.

6.6.2 Tooling

Tooling means preparing all the tools required for the automated MPD operation that may be different for each operation depends on the drilling plan above. The automated MPD tools illustrated briefly in chapter 3 for automation tools and in chapter 5 for MPD tools. Choosing the suitable tools for each operation association with the operation requirements is a very important issue to success the operation.

In addition to the automation and MPD tools, there are tools relating to monitoring and analysis of the operation process such as the human machine interface HMI tools, measurement wile drilling tools MWL, logging while drilling tools LWD, sensors, control room/cabin, and so on. Figure (&.6) shows a control room

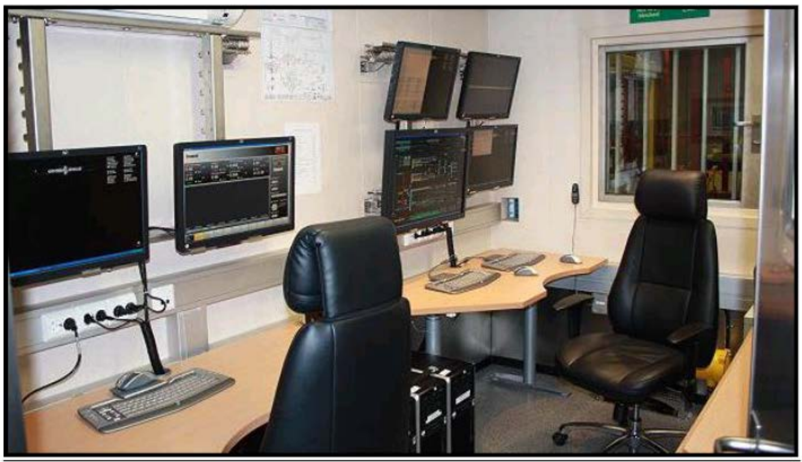


Figure 6.31: control room (Grebstad, 2014)

6.6.3 Modeling

Modeling is an essential and vital part in the automated MPD that effecting the automation efficiency of the system in a high level. The automation models created depending on the drilling requirements of the MPD operation and following the mathematical approach of the physical parameters of the operation. There are many models used in the automated MPD that requires for continuous analyzing and comparison to the measured value to update the set point value for the model. Chapter 4 illustrate briefly the different models used in the automation drilling.

The sensitive and central issue effecting the modeling performance is the data management relating to activate and update any model especially for the dynamic models that using the feedback and feedforward controllers in its functionality. The poorness in the data acquisition effecting the model function and leads to reduce the automation system efficiency that may leads to serious unwanted drilling and control consequences such as loosing of well control.

6.6.4 Processing

The automated MPD has a large number of processes starting with the connecting to the on rig activities down to the bottom hole through the wellbore and up again to the surface or subsurface through the annulus. Therefore, it is important to identifying the processes in the planning and design phase as a process sequence according to the drilling program. The most related processes to automation are three main processes:

- Drilling
- Connection
- Tripping inn and out

The automated processes through drilling can be recognized as the events during drilling such as mud mixing, pumping rate, rate of penetration ROP, flow rate, hole cleaning, and so on. That processes that affecting the drilling parameters such downhole pressure needs to be treated by automation to regulate the effect or update the control set point.

The connection process leads to change in the drilling parameters that required to manage by automation and the same thing related to tripping process. Most of the MPD processes described in the previous chapters.

6.6.5 Measurements

Automated MPD requires a set of measurements along the wellbore to measure many drilling parameters for monitoring and use the measurements in the models to compare them with the calculated data to update the set point of the model.

The measurement tools used in the wellbore are:

- Measurement While Drilling tools (MWD)
- Logging While Drilling (LWD)
- Sensors
- seismic tool while drilling
- Annular Pressure While Drilling Measurements (APWD)
- Stick/slip measurement
- Four-axis shock measurement

These tools can measure the following parameters:

- Parameters measured by MWD:
    - Rock formation type
    - Density
    - Porosity
    - Rock fluid pressure
    - Oil, gas, water and condensate existence, location and concentration
    - Trajectory pre-planning and analysis
    - Directional survey measurements
    - Well azimuth and inclination angle
    - Pressure fluctuation

There are many different types of MWD tools used today, that associated to the well type, data transformation speed, and many other features related to the measurement tools. The tools available in different sizes according to the wellbore size.

- Parameters measured by LWD are the petro-physical data
- Sensors measured parameters
  - ➢ Surface sensors measure:
    - ✓ Depth
    - ✓ Weight/torque
    - ✓ Pump pressure
    - ✓ Pump stroke
    - ✓ RPM
    - ✓ Flow in /out
    - ✓ Drill-monitor
    - ✓ Bit monitor
    - ✓ Gas-detection
    - ✓ Formation-pressure monitoring (sometimes)
    - ✓ Fluid temperature, density, and conductivity
  - ➢ The annulus pressure while drilling sensors (Schlumberger , 2010)
    - ✓ Pressure inside a narrow operating margin
    - ✓ Shallow water flow detecting
    - ✓ Tripping procedure optimizing
    - ✓ Monitoring barite sag
    - ✓ Motor performance
    - ✓ Leak Off Test LOT
    - ✓ Influxes from sweeping
    - ✓ Kick and influx detecting
  - ➢ Downhole/drilling path sensors
    - ✓ Temperature sensors
    - ✓ Borehole pressure sensors
    - ✓ Fluid flow sensors

6.6.6 Analyzing and simulation

Automated MPD required simulation and analyzing the measurements done during the drilling operation for many purposes such as:

- Using them in the models for update the set point for the model
- Monitoring the operation to avoid any drilling problems
- Evaluate the operation performance generally and the performance of each part of the operation to use in the operation itself or a data for the future planning for the operations.

Simulation and analyzing used also to optimize and develop systems performance through study the results of the system and add and remove some parameters to find the effect on the entire system. The result may used in the next operation to show and analyze the effect on the system and the operation.

SINTEF is the most popular simulation Center in Norway that dealing with monitoring, analyzing and simulating data. The big idea lays on the fact of the importance of real time data analyzing and simulation to evaluate and optimize drilling operations. SINTEF created a real-time integrated drilling simulator to define, monitor, analyze, simulate and interpreters the following drilling parameters as fig. shows :

- Flow
- Torque and drag
- ROP
- Wellbore stability
- Pore pressure

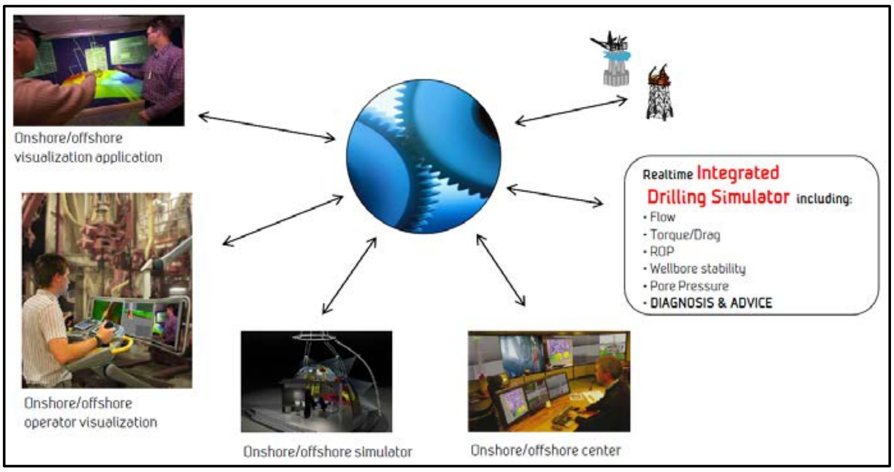


Figure 6. 32: interpretation of drilling data in real-time. (SINTAF, 2012)

6.6.7 Trust

A lot research papers and projects just accumulated on an archive rack at the end and being a number added to many other numbers with no use. These papers, projects and ideas used a lot of time, potential and money as well, which regrettable didn't presented forward to used practically or stopped in a specific level while it may go further forward. The next question coming in mind, why?

One of the answers would be that is some important thing missing in these projects, which is trust. Trust is one of the keys to implementing and developing any new technology. The oil and gas industry is a complicated, high expensive and three parts industry (operator, service and drilling) that make using new technologies difficult and cautious.

Automation is a technology come to solve many hard drilling problems with new bold ides and methods. The same thing almost valid to MPD technology. With combination of these two bold effective technologies, the result is amazing, but the factor make this combination of automation and MPD stumble to develop or more applicable in the oil and gas industry is trust.

Automated MPD is a sensitive operation implemented in sensitive drilling situations that required high level of trust to be confident in the oil and gas industry. This trust could be obtained by increasing the level of safety, reduces the system failure possibilities and analyzing the weak sides of the technology.

Every technology has the probability of failure and automated MPD has its probability of failure, which may decrease the trust level in this technology by the industry. To increase the trust level of the automated MPD, several suggestions available:

- Includes trust factor in the preplanning and predesign of automated MPD.
- Define and analyze failure modes in automated MPD and create failure mode solutions and substitutions used as an emergency plan.
- Consider the trust factor in the automated MPD technology development strategies.
- Build bridges between the three oil and gas industry parts (operator, service and drilling) to enhance the automated MPD performance to support trust factor in this industry.

6.7 safety and risk management in automated MPD

Safety is one of the main issues of using automated MPD additional to many other issues such as economy, reducing non-productive time NPT, efficiency and so on. Safety includes all relating to the automated MPD operation such human, tools, process and environment.

After Macondo accident in 2010, risk management became a vital issue in oil and gas industry in general, and in drilling specifically. According to google Wikipedia, risk management defines as **"Risk management is the identification, assessment, and prioritization of risks (defined in ISO 31000 as the effect of uncertainty on objectives) followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events or to maximize the realization of opportunities. Risk management's objective is to assure uncertainty does not deviate the endeavor from the business goals".**

There are many software today about risk management and many methods covering the risk management issues. Risk management related to the drilling risky problems that is hard to control and has serious risk consequences. Automated MPD, more or less, solving most of the risk problems related to drilling and this arise a question of is it worthy to implement risk management analysis when the most of risk problems could be solved by the system itself?

According to the advance drilling methods use for modern wells, which means wells that required high technical drilling methods such automated MPD applications, is a high controlled drilling methods that mitigate and/or eliminate drilling risky problems may not needs to use a risk management program or analysis. Moreover, there is a suggestion of choosing between using risk management or just implementing the modern drilling automated methods. In cross of that, the industry start using the real-time risk management to analyze risk earlier and find solutions to then to be included in the operational plan.

Figure (6.8) shows a closed-loop drilling system with implementation of automation with a gas chromatograph as a risk management added option to the syste.

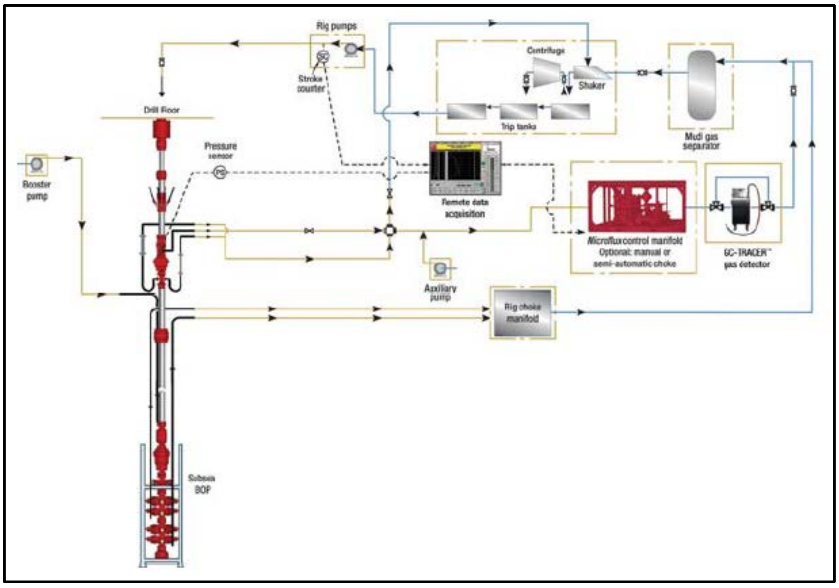


Figure 6. 33: Closed-loop drilling system.

(Hannegan, 2011)

Another example shows in fig. (6.9) of a drilling system using a supervisory Control and Data Acquisition System as combination between automation and risk management.

Risk management required a Human Risk Analysis (HRA) to analyze the risk events, causes, and solutions as a part of the drilling operation tasks to ensure high safety during the operation. Another type of risk analyses related to human error is Human Error Identification (HEI) that analyze human errors and predicting human error in the dynamic complex systems such automated MPD.

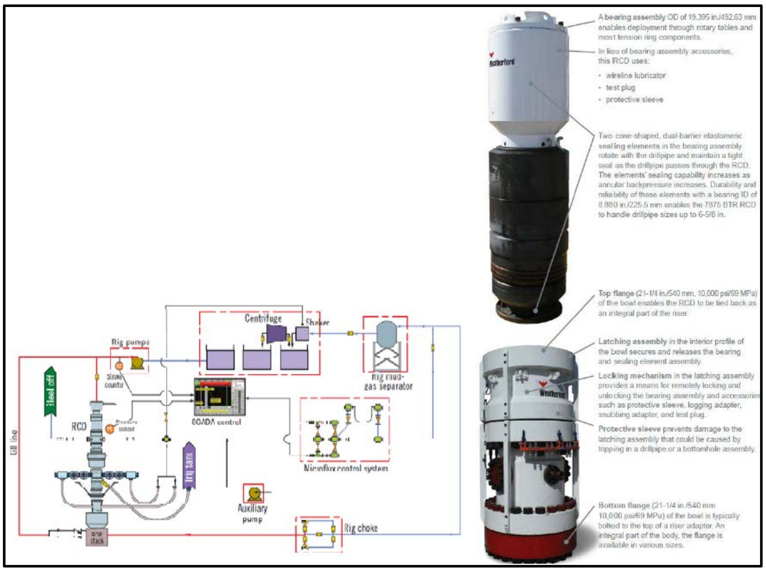


Figure 6. 34: SCADA control system. (Hannegan, 2011)

6.7.1 Safety

The automated MPD feature based on controlling the drilling operation to prevent any event may leads to safety incident such as kick that may lead in the worst scenario, which is blowout that is a very serious safety issue, which includes human, safety and environment HSE issues.

Well control is a safety issue that including of

- Loss of well control
  - kick
  - Lost circulation

Kick occur when the well pressure less than the pore pressure in a high permeability formation that lets the formation fluid influx to the well. This influx is typically gas that migrates upward if it not controlled in the right time. Migration the gas to the surface leads in the worst scenarios to gas blowout, which considered as a HSE disaster. The reasons causes loosing well control are:

- Swabbing
- Surging
- Insufficient mud weight
- The well is not full of fluid

Loss circulation is occur when the well pressure higher than the pore pressure that leads to flow the drilling fluid into the formation especially in the high permeability formations such as sand that may leads to many drilling problems such as well collapse, formation fracture because of pressure difference inside the well.

Automated MPD main task is to ensure well control to ensure safety additional to other targets of the operation. Safety divided into the following:

- Human safety
- Equipment safety
- Process safety
- Environment safety

Drilling operation such as any other operation connected directly and indirectly to the division above. When it concern human safety so it is related to the rig automation that connects to automated MPD technically in case of using automation on rig. In this case, it has to be some process connection between the rig operations and the downhole operations. According to rig automation, safety relating to human and equipment, while automated MPD is relating to all safety issues above. It is right to say that automated MPD enhanced safety level in drilling industry because it ensure prevention and mitigation of the reasons reducing safety.

Figure (6.10) shows the Bow Tie safety model used in drilling to ensure safety. This model illustrating the general hazard diagram for any event in drilling and the safety barriers required to mitigate or eliminate the hazardous event may occur during drilling.

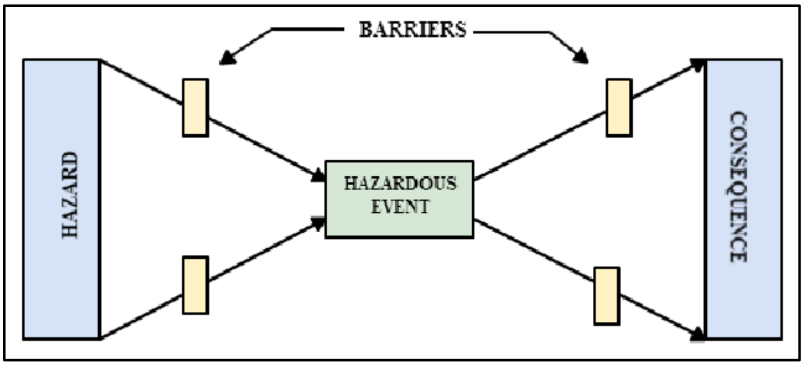


Figure 6. 35: BOW Tie safety Model. (Grebstad, 2014)

6.7.2 Human error

During history of drilling operations in the oil and gas industry, the human performance was one of the important reasons of develop and optimize the technology of drilling operations. In addition, one of the aspects of human performance is human error. In any operation, there is a range of error acceptance that have not to exceed to ensure the operation performance. This operational approach valid both for the technical/mechanical error and for human error. Human error leads to losses in safety, economy and productive time, thus technology was looking always, and still, to find to reduce, if not remove, human error.

Automated MPD is one of the technology that based on eliminating human error additional to the difficulty of drilling cases that couldn`t be drilled by the conventional way of drilling with a big dependability on human and high risk of human error. Therefore, automated MPD technology found the solution to develop the relationship between human and system/machine, which called human machine interface HMI.

Human role could be never non-exist in the drilling environment even with the high-level automated systems because of many reasons such as:

- There is no perfect automated system yet and it still a risk to depend on automation completely.
- Human role is important to monitoring the operation and making decision in the critical situation such as:
    - Failed of automation system for any reason
    - High deviation of the automated system from the ordinary set point
    - Interaction of the automated system with another operations/systems
    - Leak of data acquisition
- It is not wise in the oil and gas industry to depend completely on automation.

Huma role in automated MPD established by the human machine interface HMI that gives the user/operator the ability of controlling the entire system by a central control panel or any other tool that ensures the interface between human and machine. Figure (6.11) shows a communication structure between human and machine that illustrate the roles of different partners in the drilling operation.

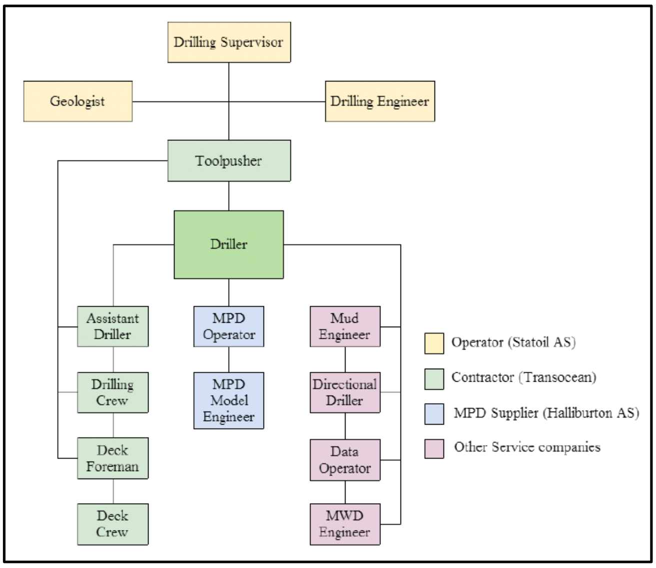


Figure 6.36: HMI communication structure. (Grebstad, 2014)

In the complex drilling system, the HMI describes as teem of many engineers and technicians working both offshore and onshore. In automated MPD, human machine interface (HMI) requires continuously evaluation and optimization that may ensures by a specific operators training program to updated to the new technologies and system coming up in the industry.

Crew training is one of the most important issues in the future work of the automation applications to be able to handle the new technologies. Automation crew, if we ca call it like this, must have the full understanding of the operation aspects and the entire operation to ensure the ability of making decisions in the critical situations. Oil and gas industry working on develop the HMI systems that is important for the industry because of the important role of the operator in the drilling operation even if the operation is highly automated.

Human error divided into two types:

- Active failure that is connected to the operator that has the direct contact to the system

- Latent errors than represented the error made by a decision maker or poor designed system.

Both of these types of error remediated by increase the crew cognition and knowledge about the new technologies and systems. In my opinion, it is important and necessary to develop the automated MPD crew or any new technology crew to be in the level, if not higher, of the new technology. Automated MPD required a crew of multi specializations that can make the right decision in the critical situations.

6.8 Automated MPD limitations and suggestions

MPD technology is a modern drilling technology that facing many operational, technical, and other limitations. Automated MPD is more complicated and has more limitations as a summation of MPD limitations and automation limitations. Chapter (5) illustrating in section (5.4) most of MPD limitations, but in this chapter will be more focusing on the most affective limitation on the automated MPD.

In general, limitations divided into two main groups, technical limitations and data limitations. Technically, the most affected aspects on the automated MPD operation both currently and fro future are:

- Rig consideration
- Crew and crew training consideration
- MPD variations consideration
- MPD tools association with automation

Data limitations affecting the automated MPD applications are:

- Data acquisition
- Human machine interface HMI
- Real time measurements

6.8.1 Rig consideration

The automated MPD required an associated rig specification with the drilling operations performed by the automated MPD applications. Automation tools, equipment, control cabin, etc. are a new requirement on rig that may need to take in consideration in the different drilling operation stages.

Even the MPD operation as a drilling operation is different in rig requirement than the conventional drilling method, which makes some intersection between the drilling method used and the rig specification.

The automated MPD is a modern and sophisticated drilling method that has the ability of continuous development and optimization. The rig requirement is a direct connected to the operation that needs to optimize continuously also to follow the automated MPD optimization. The oil and gas industry is an expensive industry additional to many other issues that any forward technological step takes approximately long time of study to be taken. Therefore, the rig development forward step constraints is one of the issues affecting the MPD operation generally and specifically the automated MPD.

The MPD equipment that required rig consideration are:

- Chock manifold
- Telescopic joint
- RCD
- Surface Annular
- Flow spool
- Top of Marine Riser
- Circulation sub
- Etc.

The MPD applications are many and it is hard and expensive to build up a common rig that has the ability to cover the different MPD applications requirement. Usually, rig design and structure is operational related project that make it unique for each rig and designing an MPD related rig is a huge engineering task. The future development dream concern the rig consideration is to design and build a well-suited rig to the MPD application with less possible scale and cost.

The automation requirement on rig is another issue related to rig consideration where some tools, equipment, and software data requirement. These requirements are not huge but sensitive for the drilling operation that required careful design and installation. Another issue related to rig consideration is the crew required for the automation process and the effect of automation on the personal on the rig.

Rig automation is a rig consideration when it connected to an automated MPD application. All the above issues will coming in the discussion to indicate the design, planning, and execute the drilling operation.

6.8.2 Crew and crew training consideration

Drilling crew is one of the important limitations in the automated MPD especially at the current semi-automated level of automation. The reason is that the MPD operation used for the critical well drilling situations such narrow pressure window, high temperature high pressure HTHP wells, high depth wells, and so on, where at these drilling conditions, the drilling problems are very critical to occur and the results extremely dangerous. The drilling problems such kick, losing circulation, well instability, etc. required high-level control and monitoring to make the right decision at the correct suitable time.

One of the reasons of using MPD automation is the human/operator error during drilling especially those that lead to the worst drilling problems scenario such as blowout. However, drilling crew still suffering of using the new technology because of Skill Lake, knowledge poorness, weak experience with the automation generally and automated MPD especially.

At the same time, the new technology is the reason of all the reasons mentioned about the drilling crew.

MPD and automation required a new stuff of operator, driller, monitor, automation man, etc. that necessary for the new technology. New crew strategies, new training programs, new crew level associated with the new technology and may develop the current crew to meet the new technology requirements.

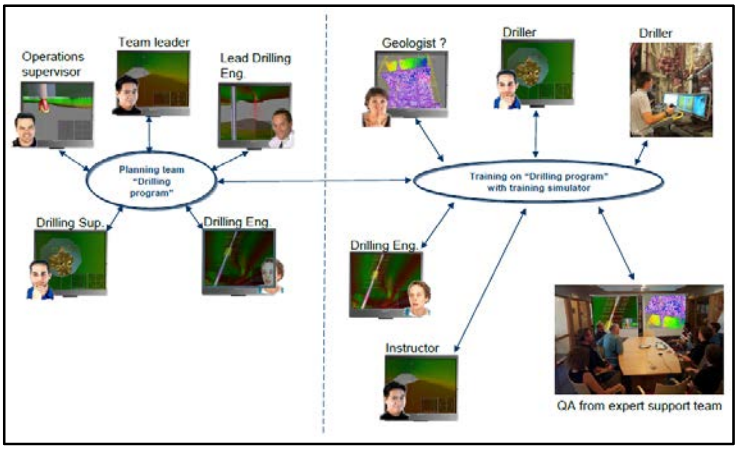


Figure 6.19: Crew training simulator (SINTEF, 2007)

6.8.3 MPD variations consideration

MPD consist of many variations applications, each used in a specific drilling operation associated with the well condition. These MPD applications illustrated in chapter (5) in section (5.2).

The MPD variations consider as automated MPD limitation because of following reasons:

- The rig capacity and tool integration with MPD applications
- MPD variations are not suitable in some drilling areas and conventional drilling preferable especially areas that add more risk issues to the exist issues.
- Difficulty of choosing of similar applications implementation for one drilling activity.
- Logistic preparation and rig requirements for the different MPD variations difficult to reach on one rig.
- Automation for different MPD variations may require additional preparation and extra equipment.

The suggested solution for MPD variation limitations is to customize a study or analysis in the predesign phase to indicate the solutions suitable for this issue according to the drilling operation performance. Additionally, out of the drilling operation, studying these variations and their field of use according to the different drilling cases, drilling problems, automation methods, drilling and automation tools, and any other related aspects will lead to determine more and more practical solution suitable for the current and future industry demanding.

6.8.4 MPD tools and variation association with automation

The association between MPD tools and variation is difficult to reach in most of drilling operations because of the following reasons:

- The unpredictable nature of the drilled well that may need more than one MPD application in the well.
- The different required automation models in different MPD applications

- Different MPD tools requirements for different applications associated with automation
- Rig requirement could not currently cover the various automated MPD application together
- The complexity of combined many application together in one drilling operation, which means reduce the automated MPD profitability compared with the conventional way of drilling.

The solution may suggested is to define the general requirements that could collect the different variations of automated MPD in a drilling operation that ensure flexibility of using the suitable option of the automated MPD variations.

6.8.5 Data acquisition

High data accuracy, sensor quality, information management system (IMS), real time data, distribution control safe system (DCSS), offshore-onshore/ field- monitoring office data communication, communications protocols, and fault detection algorithm are key elements for the data acquisition system.

The automated MPD required continuously high data acquisition system to ensure a safe, profitable and effective drilling operation. The harsh drilling operation environment both inside and outside the well affecting the data transfer and the data quality as a result.

The communication protocol failure of either transfer data at the real time or poor data quality results a control efficiency that depending on data in the control models and the algorithms performance.

Any leak in the above-mentioned elements will leads to leak in the automated MPD operation, and the process facing, sometimes, such data problems. These problems consider as a limitation to the automated MPD.

The suggested solution is to build up a data control system connected to the main control system to take an action in case of any occurrence of limitation reasons.

6.8.6 Human machine interface HMI

HMI was and still a big issue affecting both the conventional drilling and automated and not automated MPD. One of the reason of continuously creating new drilling technologies is the human errors especially that related with machine interface.

Automation MPD has to rise automation level to avoid human error and rise the technical and knowledge level of the drilling crew to ensure good communication between the crew and the automation system. Whenever the automation level rises, the crew level have to be rise to ensure balance between the system level and the crew level.

This may refers to the education methods relating to the oil and gas industry generally and the automation especially. It may recommended evaluating the education relating to automation to be more relate to the specification study.

In other ward, it may possible to establish a master study program in automation depending on the bachelor study in each field of engineering. For instance, an automation petroleum engineer could have a master degree in petroleum automation depending on the bachelor degree in the same field.

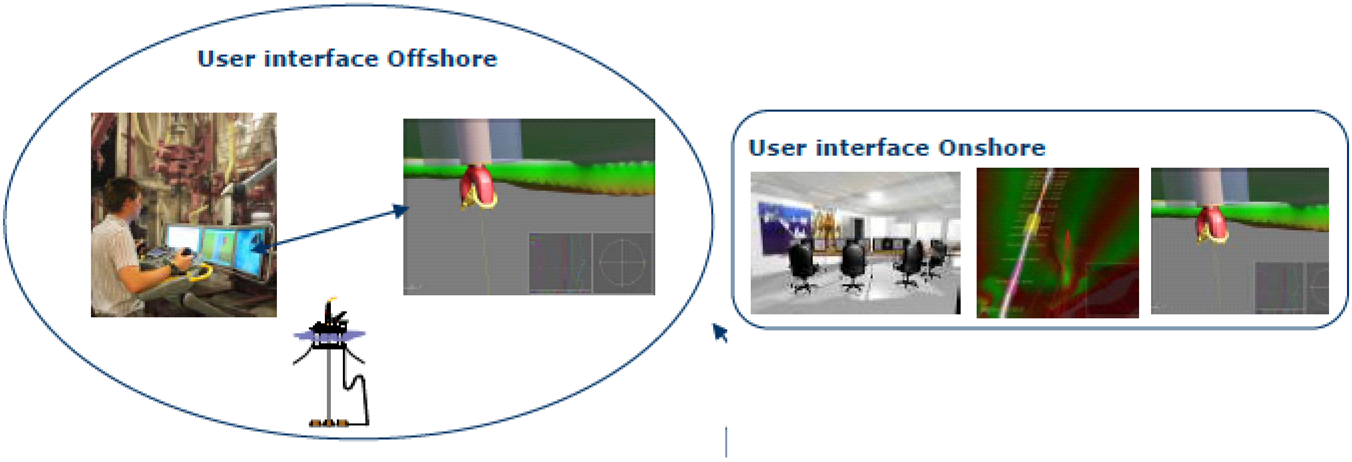


Figure 6.20: HMI onshore and offshore (SINTEF, 2007)

6.8.7 Real time measurements

Real time measurements is the artery that supplies the control system models with the required measurements data to update the set point in the models. Any unlikely data will affect the whole control operation and the drilling operation as well. High quality sensors and measurement equipment are undoubtedly required during the drilling operation.

The automated MPD facing some limitations of real time measurement that needs to be more accurate and high qualified the control system to ensure the expected result of it. High quality measurement tools and communication network will be a solution to mitigate these limitations.

6.9 SINTEF project about drilling automation (SINTEF, 2007)

SINTEF in Norwegian language means (Stiftelsen for industriell og teknisk forskning) (Wikibedia, 2010), which means in English (The Foundation for Scientific and Industrial Research). SINTEF made a project relating with automation drilling called e-Drilling/ e-Solutions, which made a search about IO perspective drilling. IO drilling means Integrated Operations related to drilling that trying to connect all the participations together in a live direct and indirect interface. This kind of integration depends on real time data and measurements for all the participants to make the drilling operation successful.

SINTEF slogan for this project was “make the invisible visible” and “make the impossible possible” (SINTEF, 2007). The project basement was to control the downhole drilling problems that costs Norway billions of Norwegian krone. This project make it possible today to use the automation models commercially in the North Sea in real drilling operations. Figures (6.2) & (6.22) shows the project concept generally based on the aspects showed in the figures.

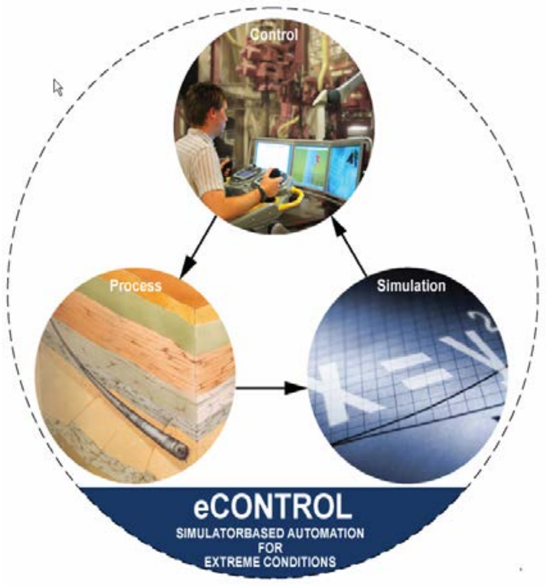


Figure 6.21: eCONTROL Automation consept (SINTAF, 2012)

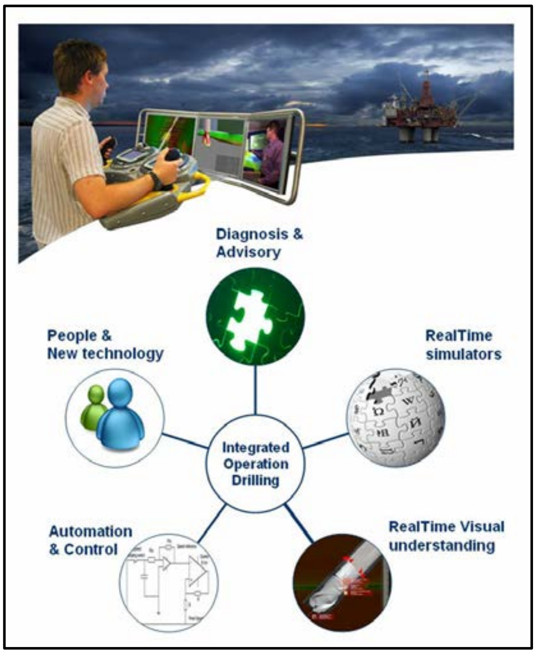


Figure 6.22: SINTEF Automation Drilling reseach (SINTEF, 2007)

Figure (6.23) shows the details of the project based on the models showed in the figure that build up the control process, automation procedure and other things related. The concept of using such system is that all the drilling operation colored in blue in the figure (6.23) will depend on the flow model that connected with all the models showed in the figure to be used in the different types of operation showed in blue in the figure. This concept depends on the following:

- Input data
- Model simulation
- Operation parameters results
- Real time measurements
- Real time simulations
- Control system
- ++++

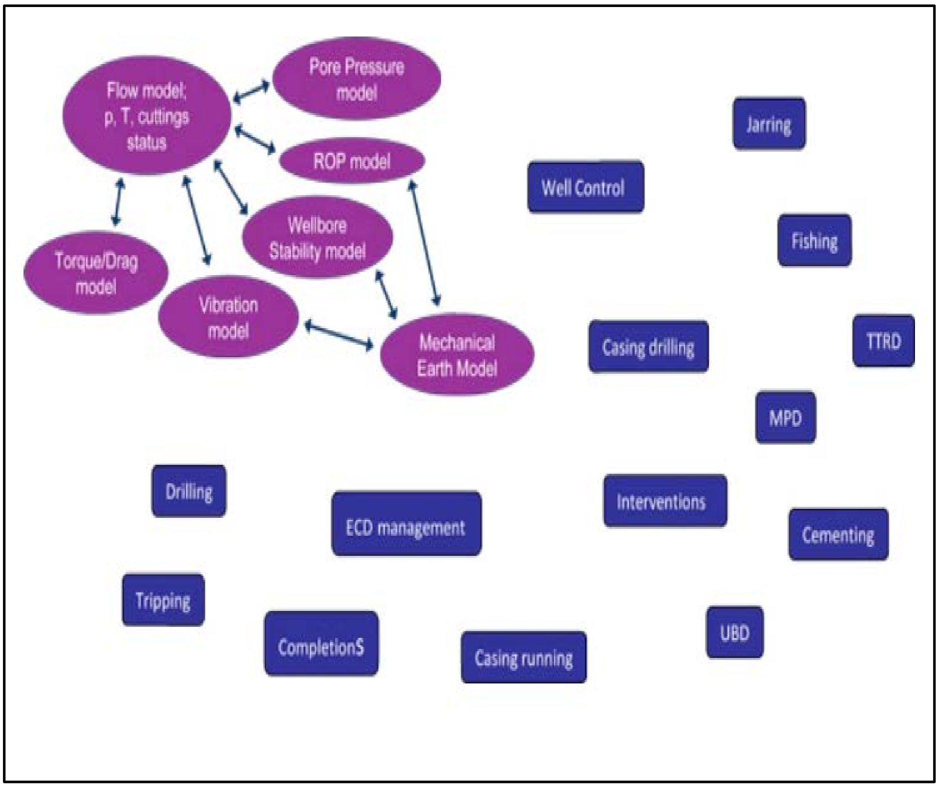


Figure 6.23: SINTEF IO project (SINTEF, 2005)

These aspects are dynamic and could be happen in one operation in one well or more.

This system is a sophisticated, practical and reliable system and according to SINTEF, it described as:

- IO in Drilling means (SINTEF, 2007)
    - RT dynamic simulations, forward looking and decision support
    - Advanced3D Visualization will transfer the work processes in well construction. Subsurface disciplines and drilling/Well will work together.
    - Wired drill pipe will greatly improve process control and provide for updating of reservoir description in real time (RT)
    - Remote controlled and Automated drilling

This system is a modern system used in the industry today but there are some questions needs to discussed and used to develop the system in the future, which are:

- Is the system general for all/most of the drilling applications? If not, so the system needs to be generalized to be valid for rest of the drilling applications in a way permits switching between system according to the well situation and behavior.
- Is there any connection between the models? Which are T&D model, vibration model, wellbore stability model, ROP model, and pore pressure model. It is clear that there is an effect of models on each other and this effect may affects the whole drilling operation, which required more concern in the future to optimize the system aspects both generally and individually.
- The oil and gas industry is a connected operations industry of three main parts drilling, production and reservoir; therefore, it is important to develop such technologies to include all the related parts in the industry together.
- This kind of technology could be a general technology to use for all/most of wells regardless the type and specifications of the well. Therefore, this consideration needs to take in concern to develop the related aspects to the industry such as rig specification, crew skills, tools management, risk management, regulations, and so on to make it more efficient and worthy.

6.9 Simplifying and generalizing Automated MPD

Automation level is the central concept of drilling automation development where the relationship between automation and drilling facilities defining the level of automation based on the oil and gas industry regulations and statements and associating with the oil and gas industry requirements and targets. The automation theory based on 6 or 10 levels of automation and according to the case studies discussed previously in this chapter, so the level of automation vary in each case study and in one of case studies automation has to different levels. To specify the level of automation, it is important to confirm using automation technology widely to indicate the level automation reached currently. Therefore, according to automation level analyzing in case studies, the level of automation could be between 3 and 6 in general with no confirming of standardize the level implementation. In other word, the automation level implemented in the automated MPD operation was exclusive to the operation itself and not a standard operation because the operations implemented to solve a specific drilling problem after fail of using the conventional drilling method. The automated MPD technology needs, as my suggestion, to be simplified, generalized and standardized to reach the target of fully automated operation based on the steps defined of the level of automation.

The automation drilling currently still a drilling problem solution more than a standard drilling method. The oil and gas industry governed tightly by many regulations and statements additional to high

Figure 6.24: The imerging between offshore and onshore operation activites by IO center (SINTAF, 2012)

misconnection between the industry`s parts (operators, service and drilling) in many of the industry aspects and especially in automated MPD, which puts many constraints to implementing any new technology.

ConocoPhillips, in one of its modern project trying to connects the oil and industry parts (operators, service and drilling) together by establishing what it called integrated operation (IO) center to keep all the parts in touch and participated during a drilling operation.

As steps forward towards full automation, many aspects needs to develop and a lot of integration required to be suggest to generalize and standardized the drilling operation especially automated MPD. There are some suggestions to take the steps up over to rise automation level in the MPD operation. These suggestions based on figure (6.12) as following:

- MPD variations
- Automation models and control systems
- Communication methods
- Automation drilling crew
- Drilling parameters

- Data acquisition system
- Drilling process

To establish a general system/diagram that can cover most of the drilling situations , if not all, for different kind of wells, the general system may has the ability of including all the requirements for each of the above aspects to ensure the ability of switching from method to another for different reasons facing the drilling operation.

The industry-developing manners relies the short, very careful studied steps for innovation and avoiding the farsighted steps. The general farsighted image may supports the short steps innovation if not adopted.

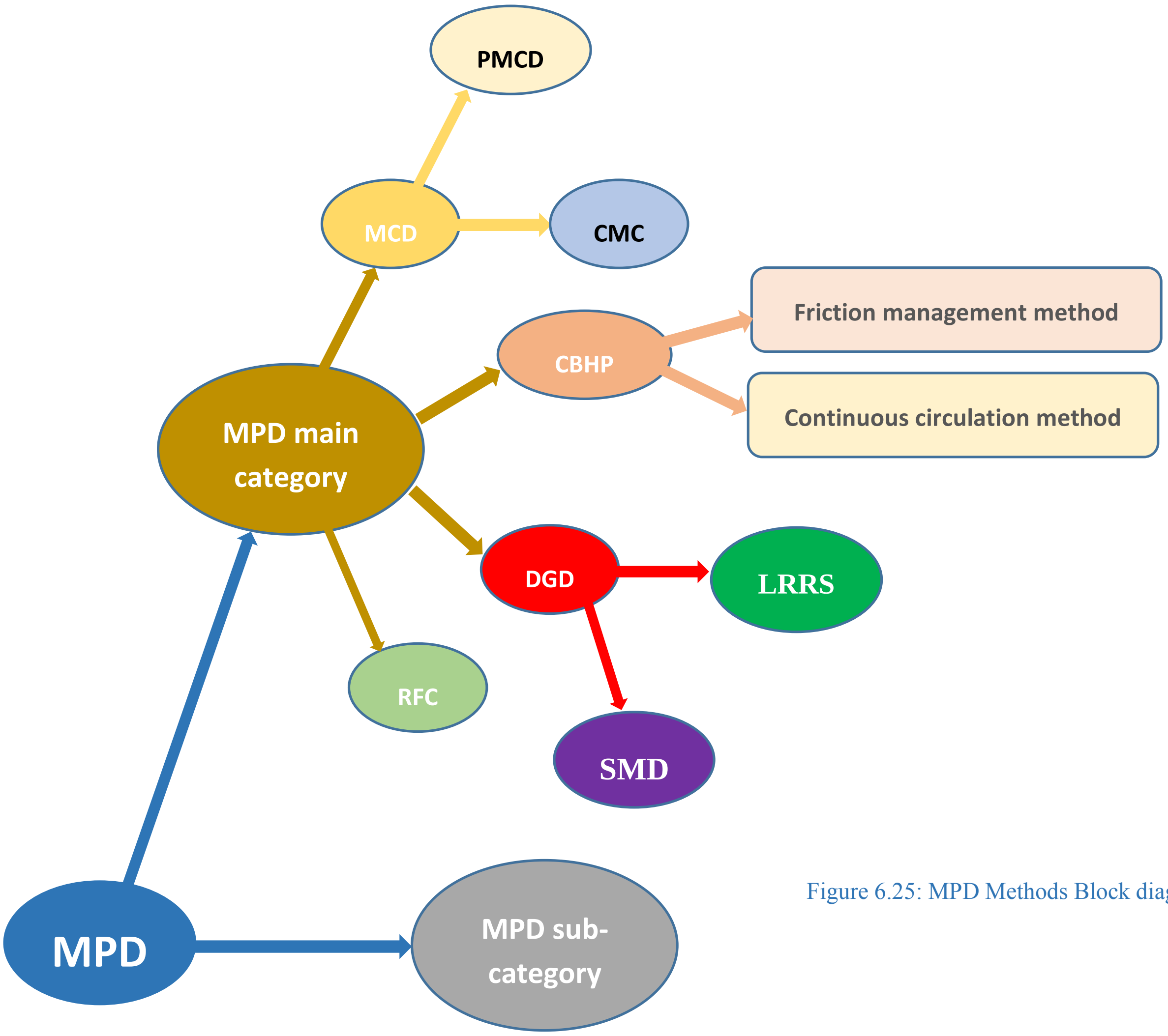


Figure 6.25: MPD Methods Block diagram

The farsighted, general and detailed manner may build up by implementing all the small individual methods have been used in the industry before. Collecting them and mixing them in a general system may give the following results:

- Develop the whole drilling industry including the expected results for economy, safety and efficiency.
- Basement for further improvement in all the related aspects
- Generalize the drilling requirements
- Generalize and standardize the drilling process

- Simplified the crew training system/program
- Integrate the different parts of the oil industry together.

The idea based on establish a diagram for each aspects of the mentioned above that shows the options in boxes. Then make a switching connection between these options to the other aspects options depending on the drilling MPD method will be used and the level of automation will be used with a flexibility of using the required automation models based on the well situation. Figure (6.20) shows the MPD variations used in drilling and the abbreviations used in this diagram found in section 5.2.

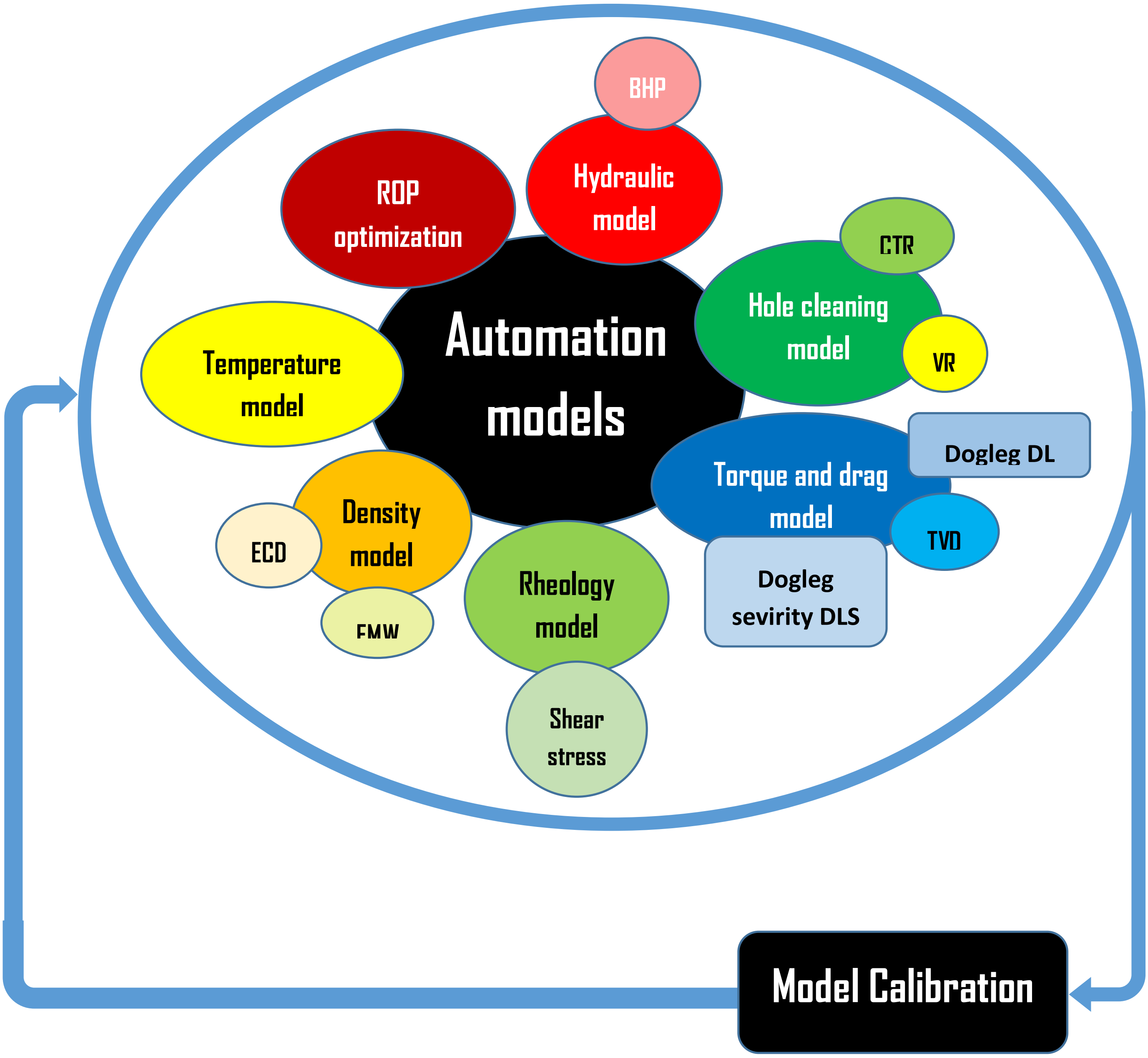


Figure 6.26: Automation models block diagram and models calibration

Figure 6.21 shows the automation models block diagram and models calibration.

The generalization of the automated MPD is a step forward to:

- Optimize the automation level.
- Customize the drilling operations and make a general system match most of the drilling operations and problems including the necessary tools and requirements.
- Integration with the current rig specification and a step forward developing the rig to match the general system requirement.
- Switching between methods of MPD according to the well situation and the drilling parameters.
- Optimizing the automation drilling crew according to the general automated MPD system.
- Easy to optimizing the data acquisition system when a standard system dealing with.
- Customize and generalize the drilling process into optional steps.
- Develop the communication method between different parts engaged with the operation and offers high integrations possibilities
- Generalizing automated MPD opens the door to generalize the other oil and gas industry fields such as production and reservoir rather than generalize the other drilling operation methods

This idea could be discussed further more in details to create a processed general block diagram includes in details all the possible automation drilling situations to make a general process system that could be programmed to control the general drilling operation.

Figure (6.12) discussed the flow diagram in on drilling operation, and as mentioned before that this flow diagram could be generalized to include the automation drilling processes and methods and programmed to be a general automation system may in the future reach the fully automation level and make the dream true to make the drilling operation completely automated.

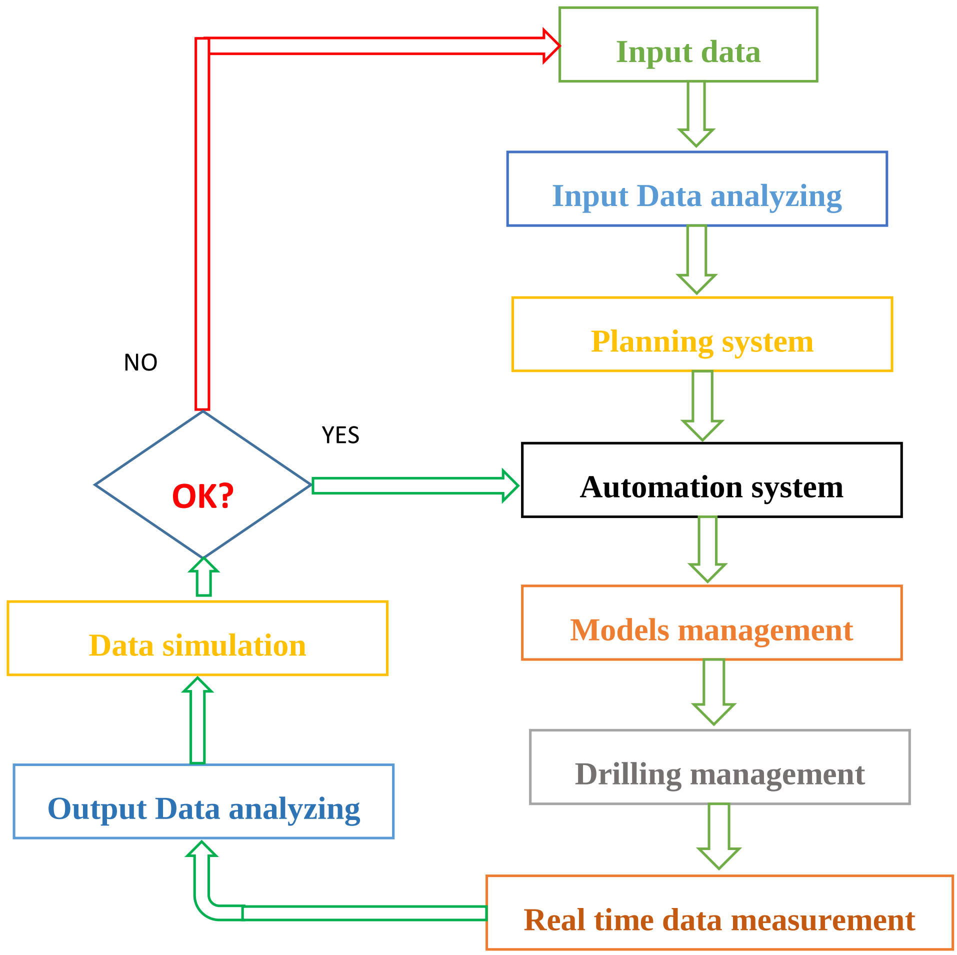


Figure 6.27: General drilling system proposal

Figure (6,27) shows a general drilling system proposal that generalize the implementation of different aspects related to the drilling operation that could be generally for different drilling cases with different drilling applications and tools with aid of automation.

Input data divided into two main types, start input data and update input data. Start input data is data that used as input in the starting of the operation preparing includes seismic data, reservoir data, depth, etc. while the updated input data is data relating to the drilling operation executed data when it facing some drilling problems and needs to be evaluated and required a new drilling plan.

Input data analyzing is kind of data filtration to avoid any unreasonable data that could lead to problems in the next stages. Choosing the wright required input data for the next stage and could be as a data archive for the system.

Planning system that is planning for the whole drilling operation with details depends on a well design software planning for each aspect in the drilling operation. Choosing the drilling application, drilling tools, and so on. Planning system is a dynamic system that changes according to the update input data.

Automation system is the system that decide the level of automation required for the operation depending on the input data and the planning system. The drilling operation may start with a conventional drilling operation until it face a specific drilling problem that requires a new planning, new models management and may requires an automation system. Depending on the drilling operation output data, the level of automation will changes to match these data requirements.

Models Management is the part responsible of build up the required models for the drilling operation depending on the input data. When the operation started, the models management will manage the models based on the results of the operation to ensure that the models used matching the operation requirements.

Drilling Management is all about drilling related aspects such as tools, crew, method, and related operations such as mud management, cementing, etc..

Drilling management connected to planning system and models management closely because of the many similar aspects in each of them.

Real time data measurement is the measurements needed to run to check the drilling operation if it safe or not. These measurements illustrated briefly in the previous chapters. These measurements will be the base of either continue drilling with the same application, using new models or starting a new plan and new drilling application.

Output data analysis that analyzing the output data of the drilling operation if it quite reasonable according to the drilling application used or it is not. This step and the next step, data simulation, accounts such a control system for the operation incorporation with another parts such as model management.

Data simulation to simulate the output data and compare them to the measured data and calculated/planned data to decide what to do in the next step.

OK? is the step to decide if the operation is ok and continue drilling either with the same drilling parameters or need to manage models to changes some drilling parameters. If not ok, the option will be starting a new planning and evaluate the drilling application could be used for the next well situation.

Chapter 7

Conclusion

The oil and gas industry is busy continuously to find and develop new technologies to meet the industry requirements such as safety, economy, and efficiency. The serious accidents happen, the unstable prices of oil and gas, the less efficiency led to high non-productive time and many other reasons led to motivating the industry to develop the current technologies find new technologies to cope with the situation. The oil and gas industry in Norway specifically needs to focus on creating and implementing new technologies to meet the marked requirements especially that this industry in Norway working on a high quality standards level called NORSOK that consider as an expensive standard comparing with the rest of the world.

Managed pressure drilling (MPD) and drilling automation in are a modern technologies created and implemented in the oil and gas industry in the recent decades. These two technologies individually and combined had a high effect of the drilling operation optimizing and was responsible of solve many drilling problems that it was even considered as impossible to solve. In this thesis many aspects related to these two technologies have been illustrate briefly and in details to prepare to the next step that is how to generalize these technologies to meet most of the drilling applications for different well situations.

Many companies and research centers was working on develop and optimize the current technologies especially SINTEF that taken as an example in this thesis because of the amazing results they reached and commercially used in the industry. Nevertheless, according to the SINTEF report that the research still looking forward to the future optimizing, which is mean there are still somethings missing in this technology.

This thesis discussing the current technology requirements according to many aspects mentioned briefly in chapter 6 such as planning, limitations and suggestions. Additionally, the thesis discussing the SINTEF missing points and use it a basement to offer a proposal to generalize the technology to be more common and useful.

The oil and gas industry needs to modify the drilling requirements and tools to match the new technologies for instance rig specifications that needs to be modified gradually at the current situation until it completely developed or building new rigs compatible with the new technology requirements.

The industry participants, which are operator companies, drilling companies and service companies hesitate of using the new technology because of the trust factor to the new technologies. Therefore, it is quite important to show the industry participants the importance of using such technologies and the big role of then to success these technologies that required a high level of integration between them.

The oil and gas industry is a several sequential operational industry includes three main branches which drilling, production and reservoir that connected with each other directly and indirectly. In the future, it may be useful to discuss the possibility of including all these branches of oil, gas industry in one common system that has the ability and flexibility to cover the different industrial situations had the industry met, and may the industry meet in the future.

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