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Abstract

Drilling fluids are perhaps the most important feature of a drilling operation, it is a multipurpose fluid that also functions as an information channel to the surface. Traditionally drilling fluid properties like density and viscosity were usually measured manually by taking samples, but in the last couple of years the drilling operation is evolving to be more and more automated.

The theme of this thesis was to look into the possibility of having continuously measurement of viscosity and density of drilling fluid. To solve this task, a measuring system consisting of a viscosity and density sensor was designed. This included both hardware and software programming. The software has been simulated and verified, while the hardware is due for production.

This thesis is a part of the global vision of making the drilling operation fully automated, to reach this goal the rig needs real-time monitoring for every variable in the drilling operation. To make the system as efficient as possible, an automatic flushing system is implemented, and communication with existing sensors is established. It is emphasized that this thesis is a preliminary design with a vision of a future commercial product.

Abbreviations

MSS - Mud Sampling System, the system I am developing durring this master thisis.
NOV - National Oilwell Varco Inc.
MP - Mud pump
SDI - Smart Drilling Instrumentation
HMI - Human machine interface
PLC - Programmable Lolgic Controller
STL - Statement List
LAD - Ladder Diagram
FBD - Function Block Diagram
UDT – User defined data type
DB – Data Block
FC – Function Call
OB – Organization block
HSE – Health safety and environment
WBM – Water based mud
OBM – Oil based mud
SBM – Synthetic based mud
YP – Yield point
PV – Plastic viscosity
SG – Specific gravity
RPM – revolutions per minute
PSI – pounds per square inch
GPM – Gallons per minute

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1 INTRODUCTION

During my last year as a student of master in science at The University of Stavanger, I have had the opportunity to work as an intern at National Oilwell Varco Inc. As I was about to choose a topic for my master`s thesis, my employer challenged me on the following;

“Can you design a system for measuring viscosity and density?”

This would implicate both soft- and hardware design. National Oilwell Varco Inc. is amongst one of the world`s leading company in drilling technology equipment, and it is vital to work innovative in developing new technology to be able to keep up the market position. I was inspired by the challenge because working with new technology and innovation is exciting to work with. My vision was to develop a high quality system for continuously measuring viscosity and density in drilling fluid. This would not only give benefits of continuously monitoring the process, economical benefits, but also of significance of HSE.

After the instruction the report continues with a presentation of the theory involving drilling fluid. After that follows chapter three which presents the hardware design of the mud sampling system. In chapter four the software explained in details to give the reader a further insight of how the system is meant to operate. The report ends with a short discussion and conclution.

1.1 Background

The trend in oil and gas industry has changed the last couple of years. From being a conservative industry that was skeptical to new technologies, now they want to use the latest and most efficient technology. It may be because of the focuses on HSE and cost efficiency, which both have benefited of automates and monitor as much of the drilling operation as possible.

When going from manual sampling measuring to continually on-line measurement, it’s not only beneficial form a HSE view or cost perspective. It also opens up for improvements of other systems like the mud mixing system, in theory we can now automate the mud mixing proses with constant feedback from the Mud Sampling Skid.

The first stage of going from a manual sampling measuring to on-line continually measuring is to verify that the on-line matches the off-line, so that the operator relate to the off-line readings. There will take some time before the manual measurements are completely gone, but this is a small step towards a fully automated drilling rig. For now this system will function as a redundancy until there is enough experience regarding its reliability and relatability.

At the start of the thesis the scope was to look into how to measure viscosity and density as efficient and reliable as possible. The scope developed gradually from a measuring unit to an automated system.

2 THEORY

As this is a thesis in the master subjects for automation and signal processing, I will shortly describe the functions of drilling operation in order to set the system into a context.

The theory about the drilling operations is so wide, the measuring of mud has a huge impact on safety while drilling. In the following I will describe this subject more detailed:

2.1 Drilling fluid

Drilling fluids is one of the most important features in a drilling operations, it is a multipurpose fluid that also functions as an information channel to the surface. It can be compared to the human body, where the drilling fluid is the blood; it’s been pumped around by the mud pumps witch function just like the heart, the cuttings represents the bodies waist products. When the mud returns to the surface it is cleaned in a comprehensive cleaning system, which can be compared with the kidney, liver and lungs in the human body.

2.1.1 Drilling fluid circulation system

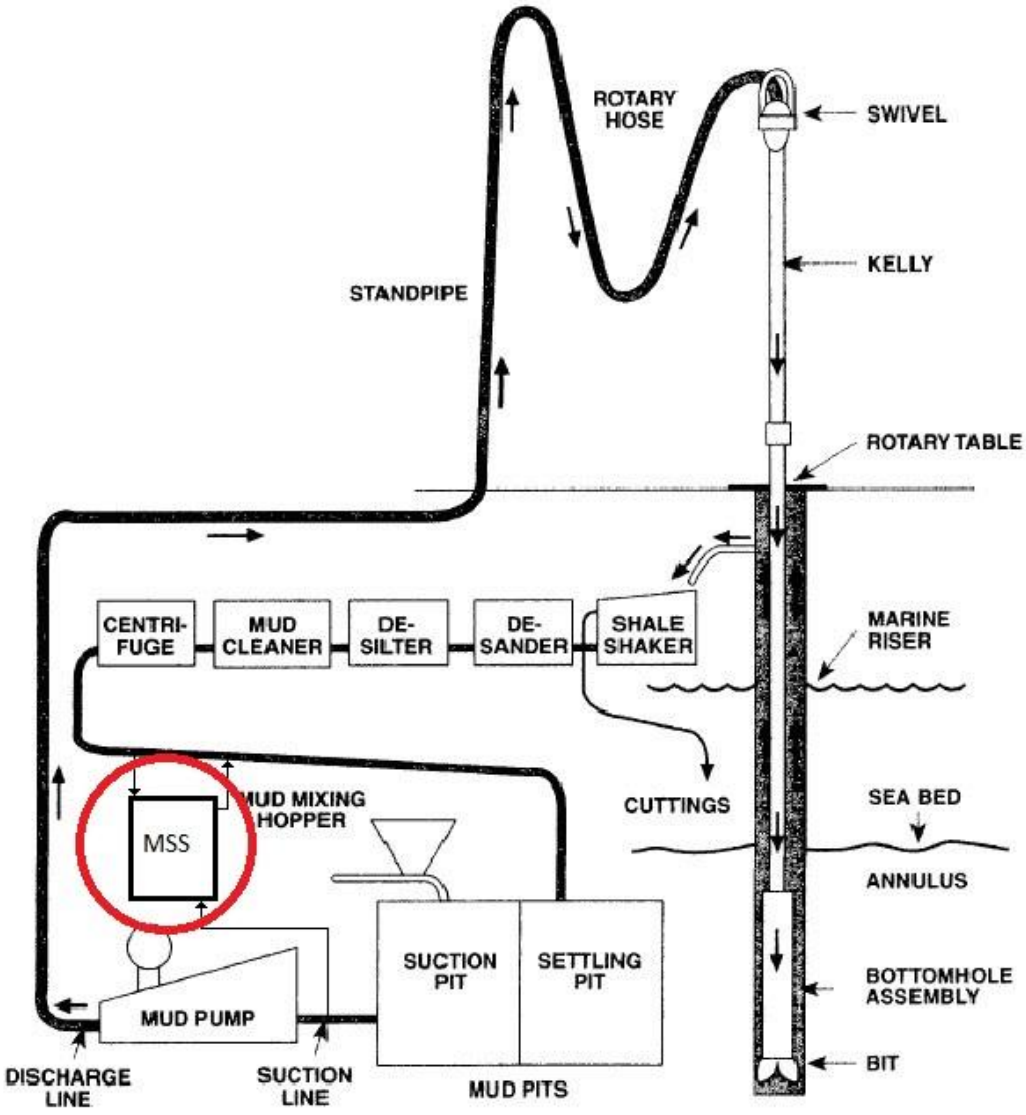


Figure 2-1 Drilling fluid circulation system [5]

The drilling fluid circulation system is comprehensive and complex, from its start in the mud pits to the bottom of the well and back up it goes through kilometers of piping, tanks and pumps. The system developed during this master thesis is directly connected to the circulation system and adding a brand new form of monitoring of the drilling fluids properties in real-time.

An explanation of the circulation system and its components in figure 2-1:

- Mud Pits: This is a large room dived into of multiple pits. The pits are filled with different drilling fluids, with different properties according to the drilling plan.
- Charging pumps: This is not shown in figure 2-1, but it is the pump that feeds the mud pumps. The hydrostatic pressure from the pits alone is not enough to achieve optimal working condition for the mud pumps. This is solved by using a charging pump that

feeds the mud pump up to 125 psi, depending on the pump. In to the well line of the MSS is connected on the suction side of the charging pumps.

- Mud Pumps: Depending on the type of rig there are between 3 to 7 mud pumps, usually they are running two in parallel with up to 3600 l/min each. They can deliver a discharge pressure up to 6300 psi which is needed to circulate the drilling fluid in and out from the well.[6]
- Standpipe: The piping that leads the drilling fluid from mud pumps to the top drive.
- Swivel: Usually a Top Drive is used which delivers the torque to the drill string that turns the bit on the bottom of the hole.
- Bit: The fluid is lead inside the drill string all the way down to the bit, where it transports the cuttings from the bit to the surface in the annulus.
- Shale shaker: When the drilling fluid returns to the rig it goes through a comprehensive cleaning system. The first step of this process is the shale shaker, it is a screen with different mesh that separates solids from the liquids.
- Desander and Desilter: Consists of hydrocyclones that separates sand form the drilling fluid.
- Degasser: Removes unwanted gas dissolved in the drilling fluid.

2.1.2 The drilling fluids function

The importance of drilling fluid properties will vary from well and formation, but generally it have the same function for most drilling operations.

The first important feature is the removal of cuttings from the bit and transporting them to the surface. The mud is flushing the cuttings from the bottom of the bit by exiting the bit via jet nozzles. The pressure the mud is exiting the nozzles is typically 50% of the mud pump discharge pressure. That is why the mud pump discharge pressure is so substantial, by the time the mud reaches the bit, 50% of the pressure is lost in the drill string [7]. Viscosity is the main property for removal of cuttings, if the viscosity is to low the cuttings will settle faster and the lifting capacity will be lower than with a higher viscosity.

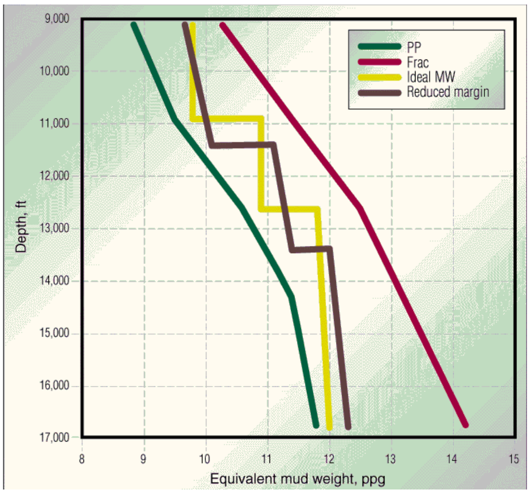


Figure 2-2 Annulus pressure (Oil&Gas Journal 1998)

Secondly it keeps the pressure in the annulus stabile, the drilling fluid pressure has to be between formation pressure and fracture pressure as shown in figure 2-2. The drilling fluids pressure is normally 200 psi over the formation pressure.

The drilling fluid also cools and lubricates the drill string and provides a buoyancy effect on the drill string and casing. While drilling the friction caused by the bit crushing the formation generates heat, when drilling deeper core temperature increases even more. The drilling fluid cools and lubricates the drilling bit, this extends the drilling bits life span.

As well as controlling the formation pressure, it maintains the stability of the wellbore and isolate fluids from the formation to minimize influx or loss to formation.
The drilling fluid is also used as transmission of hydraulic power to the bit and down hole equipment's, such as measurement while drilling equipment and turning the bit for horizontal drilling.

2.1.3 Types of mud

The behaviour and type of drilling fluid may change depending on the application and downhole conditions. Therefor there are various types of drilling fluids used by the operators, they can generally be categorized in to three types of drilling fluid.

1. Water Base Mud (WBM)
2. Oil Base Mud (OBM)
3. Synthetic Base Mud (SBM)

Water base mud is the most commonly used drilling fluid due to the fact that it's the most economical and environmentally friendly of all types of drilling fluid. While Oil base mud is more expensive, and with the risk of cuttings is not properly handled, oil based mud can be a possible hazard for the environment. Oil based mud gives the opportunity for drilling in high temperature holes and situations when there is a need of a higher rate of penetration.

Within the drilling fluid there are two important properties we need to monitor to achieve the desired tasks mentioned earlier. The first property is density, its purpose is to keep the annulus stabile while the pressure increases while drilling with the hydrostatic pressure formula.

$$p = \rho g h$$

The second property we want to monitor is the viscosity. The viscosity controls the lifting capabilities of the fluid when removing the cuttings.

2.2 Viscosity

The phenomenon viscosity was actually mentioned in Sir Isaac Newton's famous book of *mathematical Principles of natural Philosophy.* He then stated that "the resistance witch arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which parts of the liquid are separated from one another". This "lack of slipperiness" is what we now call viscosity [1].
Viscosity's unit is named after the French physician Poiseuille who studied blood flow and did extensive experiments with flow in tubes.

A fluid in motion can be seen as layers that deforms with variable speed, like shown in figure 3-3. A classic experiment is with two parallel plates with a narrow gap between them, the lower plate is stationary while the upper plate is moving with a constant speed.

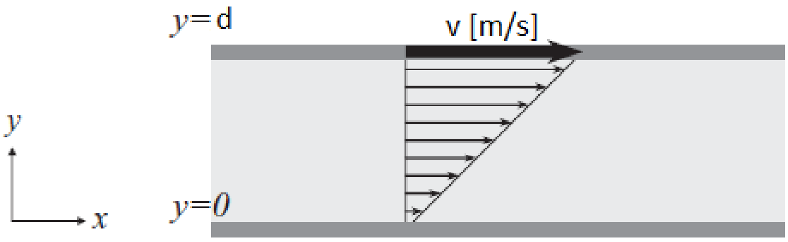


Figure 2-3 Steady simple shear flow, Newtonian fluid [3]

By definition, dynamic or absolute viscosity can be given as:

$$\mu = \frac{\sigma}{\dot{\gamma}}$$

Where $\dot{\gamma}$ is the shear rate, σ shear stress and μ the dynamic viscosity, with the unit Pa·s or cP. However, viscosity is not that simple to describe. Viscosity can be represented as dynamic (absolute) viscosity or as kinematic viscosity. As mention earlier, viscosity is the fluids resistance to flow at certain at temperature. Normally we say that a thick fluid have a higher viscosity than a thinner fluid, this is often misleading since viscosity is not a dimensional measurement. Kinematic viscosity is another way of describing the fluids properties, dividing the dynamic viscosity with its density[12].

$$\upsilon = \frac{\mu}{\rho}$$

Where ρ is the fluids density and υ the kinematic viscosity, with the unit centistokes, cSt.

Fluids are generally divided into two groups of fluids, the Newtonian and the non-Newtonian. Even though Newtonian fluids are varying with temperature and pressure, it does not vary with deformation or time. Witch make the relationship between the shear rate and shear stress linear, example of such a fluid is water. On the other hand, non-Newtonian fluids have a nonlinear relationship between shear rate and shear stress. Some fluids are shear thickening, which means that the fluids thickens when applying force to it. An example on such a fluid is a mix between water and cornstarch, if you fill a pool with a 1:10 mix ratio you can actually run on "water".

The other group of non-Newtonian fluids are shear thinning, in this group the fluid gets thinner when forced is applied. Ketchup and blood are some examples of fluids with shear thinning properties [9].

Drilling fluids are a shear thinning fluids with thixotropic property. It means that the drilling fluid returns to a semisolid state, like a gel when no force is applied to it. As for the drilling operation, this is a vital property. When there is a stop in circulation of the drilling fluid, the cutting are suspended in the drilling fluid. Without this property of the fluid, the cuttings would fall down to drilling bit and lead to a stuck pipe.

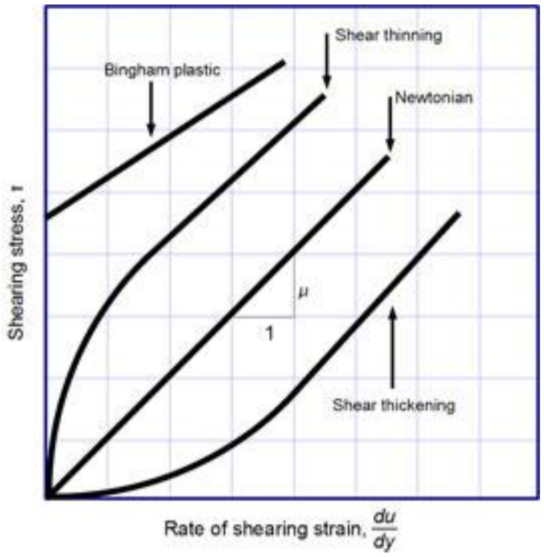


Figure 2-4 Viscosity models [9]

There are many different models of describing viscosity, but the most common is the Bingham plastic model and this is widely used in the drilling operation [12]. The Bingham plastic is a model for shear thinning fluids, it adds two new parameters from viscosity that describes the fluids behaviour. The first parameter is the plastic viscosity (PV), it is the slope of the Bingham model in figure 2-3. It is measured by taking difference of the reading at 1022s^{-1} and 511s^{-1} and describes the internal resistance in the fluid:

$$Reading\ at\ 1022s^{-1} = 50$$
$$Reading\ at\ 511s^{-1} = 30$$
$$PV = 50 - 30 = 20\ cP$$

In the drilling operation the operator wants to achieve as low PV as possible to increase the rate of penetration, and reducing the soil content in the fluid is the best way to keep the PV low.

The other parameter from Bingham plastic model is the yield point (YP), YP on the other hand is the resistance of initial flow in order to move the fluid. YP is the ability to carry out the cutting to the surface, with higher YP the better lifting capacity but at the cost of higher pressure loss of the circulating mud. With same reading as above the YP will be:

$$YP = 30 - 20 = 10\ \frac{lb}{100} ft^2$$

In combination:

$$\sigma = YP + PV(\dot{\gamma})$$

2.3 Density

Density is defined as weight per unit volume, normally we use *kilograms per cubic meter* (kg/m^3). However, in the oil and gas industry they use *specific gravity* (SG), *pounds per gallon* (PPG), *pound per cubic feet* (lb/ft^3) or even *grams per millilitre* (g/ml). Nevertheless, in this assignment SG is used as the main unit. SG is a compared weight of equal volume water. In room temperature water weighs ca. 1000 kg/m^3, which gives us:

$$SG = \frac{measured\ medium\ [\frac{kg}{m^3}]}{water\ weight\ [\frac{kg}{m^3}]}$$

$$SG_{water} = \frac{1000[\frac{kg}{m^3}]}{1000[\frac{kg}{m^3}]} = 1$$

As mentioned earlier, the density is monitored and regulated to secure the well stabilization. To prevent influx that can lead to a blow out, the drilling fluid needs to have a higher pressure than then pore pressure by at least 200 psi, shown in figure 3-2.
The pore pressure depends on the depth, the density of the formation fluid and geological conditions. While drilling the drilling fluid absorbs the cutting which increases the density, this results in some issues regarding safety and efficiency. This excessive density influence the drilling rate, experiments and field tests has shown that the rate of penetration is reduced by having a to high differential pressure between the drilling fluid and pore pressure [2].

To summarize:

- If the density is to low:
    - The well becomes unbalance making it possible to get influx as oil, gas or water.
    - The hole can collapse
- If the density is to high:
    - It can fracture the formation resulting in loss to formation
    - Decrease the rate of penetration
    - Higher chance of the drilling string to be stuck
    - Damage the well

3 DESIGN

To be able to measure the desired drilling fluid parameters, sensors need to be connected to the proses line. By the scope set in this thesis, measuring of drilling fluid properties going in and out of the well was the main task. To be able to achieve measuring on–line it would have required enormous viscometers that would be extremely costly if they even existed. The only sensible solution was to make an in-line measuring skid. It is called a modular process skid, it is basically a stainless steel frame with sensors and instruments placed inside of it. It makes it movable, smaller and easy to install on existing rigs.

The mud sampling system consist of following components:

- One measuring skid, shown in figure 3-1, with these main components:
    - Two viscometers, Brookfield's TT-100.
    - Two coriolis sensors, Micro motions's CMFS 075M.
    - One Wilden diaphragm pump.
    - One Blacoh pulsation dampener.
- One pump skid, shown in figure 3-2.
- Eight butterfly valves.
- Two ball valves.
- Two pressure relief valves.

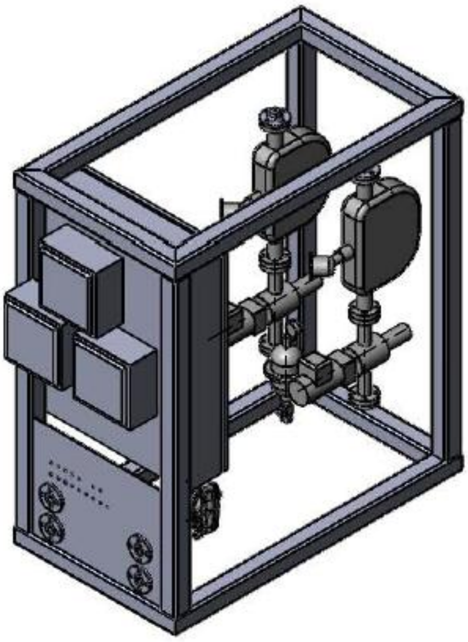


Figure 3-1 measuring skid [13]

The mud sampling skid is placed in the process as drawn in to the figure 2-1. The placement on the rig will most likely be in the mud pit area, where there is shorter distant from the return gutter and from suction side of the charger pumps.

Both the processes connections have the same valve setup, two butterfly valves, one ball valve and a pressure relief valve. The first butterfly valve is to open and close the mud into the skid. The second set of valves is for the flushing water. From the rig water supply, the pressure can be up to 10 bar and when the diaphragm pump can only handle 0.7 bar on suction, the pressure have to be reduced with a pressure relief valve. After the pressure relief valve, there are two valves in series to ensure that no water will mix with the mud. First there is the ball valve, the advantage of the ball valve is the good seal, making sure there is no water leakage. The reason for having a butterfly valve after the ball valve is the implication with the gasket on the ball valve in contact with mud, mud will practically eat off the entire gasket of a standard ball valve over time.

In appendix B the integration of the mud sampling system is roughly illustrated. As mention above, the limitation regarding the diaphragm pump and inlet suction pressure is set at 0.7 Bar. On the in to the well sampling line, the connection point is located seven meters under the mud pit room. This raised a question about where to place the pump for in to the well sampling line. According to the pumps data sheet, the pump has suction lift capacity with water of 4.7 meter dry and 8 meter wet. When the system is designed to sample on drilling fluid, which can have more than twice the density compared to water. With the suction lifting capacity reduced to less than half, there is no way to place the pump inside the skid. The other issue to move the pump lower than the mud pits is the hydrostatic pressure generated from the mud pits, regarding the limitation of the pump at only 0.7 bar on suction.

To make sure the pump works in all conditions the pump had to be put in a separable pump skid, as shown in figure 3-2, it would be located approximately 3 meters under the maximum level of the tank.

$$p = \rho g h$$

$$h = \frac{p}{\rho g}$$

$$h = \frac{70000\ \frac{kg}{s^2}}{2400\frac{kg}{m^3} * 9.81\frac{m}{s^2}}$$

$$h = 2.97m$$

Where the maximum pressure p is 70 000 Pa and the worst-case density ρ is 2400 kg/m^3, this will give us the maximum suction head in meter.

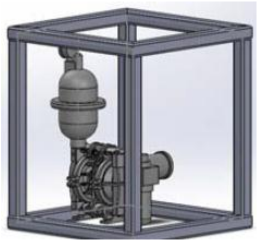


Figure 3-2 sampling pump skid [13]

3.1 Viscosity sensor

There are more than one way to measure viscosity but they all follow the same basic principle. A viscometer usually apply a force or a velocity at a surface in contact with the desired fluid. The goal of this is to convert the force to shear stress and velocity to shear rate, which gives out the viscosity.

When adding a brand new viscosity measuring system to a rig, the operator wants the reading to be relatable to the existing off-line instruments reading.
The most common used on today's rigs for off-line viscosity measurement is the FANN35. It is taking manual samples and measure from 3 RPM to 600RPM, matching the shear rate values shown in figure 3-3. In order to replicate the off-line measurements a sensor capable of measure at the same shear rates is necessary.

There are three main types of on-line viscosity measurement instruments [12]:

- The rotation geometries instruments, example:
    - Brookfield's TT-100
- The speed of falling or pulling the fluid, example:
    - Cambridge electromagnetic piston viscosity sensor
- The vibrating element viscometer, example:
    - Nametre viscometer

Common to all types of viscometers is that they measure the same physical property, force applied from the fluid to measuring element. Usually for the vibrating element there is a fork that is oscillated, and the force to keep the fork oscillated in the fluid is related to the viscosity. The same goes for the Cambridge electromagnetic piston, which measure the force from a piston that is being pushed and pulled in to the fluid.

The first element when choosing a measuring instrument is what type of fluid the instrument sensor is supposed to measure. In this case, it is drilling fluid which is a non-Newtonian and shear thinning fluid.

The Cambridge piston sensor and the Nametre vibrating element can both measure non-Newtonian fluids, the only problem is that measurement is dependent of the flow and is not directly relatable to the shear rates in figure 3-3. To relate the off-line measurement, the apparent viscosity $\mu(\dot{\gamma})$ has to be measured in the same shear rates.

$$\mu(\dot{\gamma}) = \frac{\sigma}{\dot{\gamma}}$$

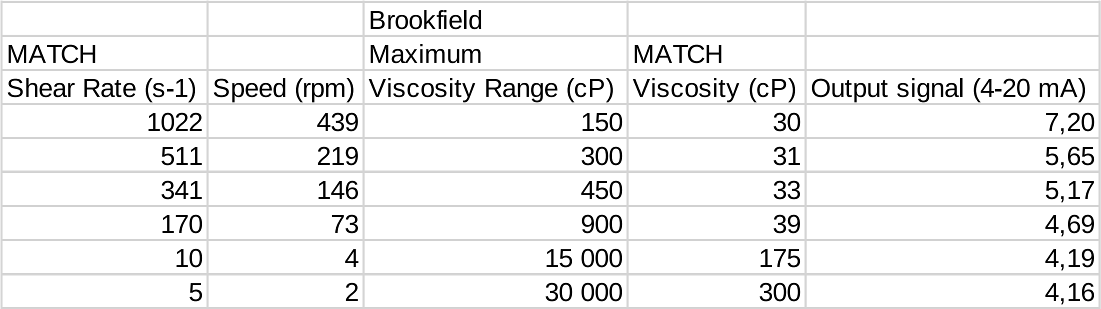
When using the piston sensor and the vibration sensors the system has no control on the shear rates in which the viscosity is measured. The only solution to this problem is to have a variable speed sampling pump setup to regulate to flow accordantly to the shear rates measuring cycle. This would require a flow ramp-up system in a different pump with feedback from the coriolis flow sensor, to ensure the flow is correct. That solution would be a highly unstable system for measuring viscosity at six different shear rates.

Compared to the other sensors the Brookfield TT-100 viscometer has its own motor that can be PLC controlled to variable speeds [11]. This allows the viscometer to measure at the same shear rates as the off-line table top viscometers used today on drilling rigs.

On the TT-100, the drilling fluid flows through the inlet in to the measuring chamber, where some of the fluid finds its way between the rotor and stator driven by the motor (figure 3-4). The force on the torsion element is measured and converted to viscosity in correlation with the motor speed. The first calculation transforms the torque to correspond with the readings on the off-line instrument line the FANN35. Theses readings are called Theta. The Theta values are converted to dynamic viscosity as shown in the formulas below and figure 3-3.

$$\theta = \frac{out\ signal(mA) - 4}{16} * Max\ viscosity\ range * \frac{Fann\ Speed}{300}$$

$$\mu = 300 * \frac{\theta}{Fann\ Speed}$$



		Brookfield		
MATCH		Maximum	MATCH	
Shear Rate (s-1)	Speed (rpm)	Viscosity Range (cP)	Viscosity (cP)	Output signal (4-20 mA)
1022	439	150	30	7,20
511	219	300	31	5,65
341	146	450	33	5,17
170	73	900	39	4,69
10	4	15 000	175	4,19
5	2	30 000	300	4,16

Figure 3-3 TT-100 test sheet [10]

For the mud sampling system the Brookfield's TT-100 viscometer is the most suitable sensor for the measuring of viscosity, YP and PV. Brookfield engineering company are the oldest manufacturer of commercial rotational viscometers in the world, giving it the reliability with using a well-known manufacturer in a new system [11].

One of the biggest concerns with measuring on drilling fluid is the wear on the instruments, drilling fluid as mention earlier is a shear thinning fluid, which thickens up when there is no circulation. Cleaning an instrument on a regular basis without disassembly, it is a key-selling point for a sensor. Brookfield have a special designed housing for cleaning-in-place supplied by APV. This feature is used for achieving the smart automatic cleaning system, which is included in the mud sampling system [11].

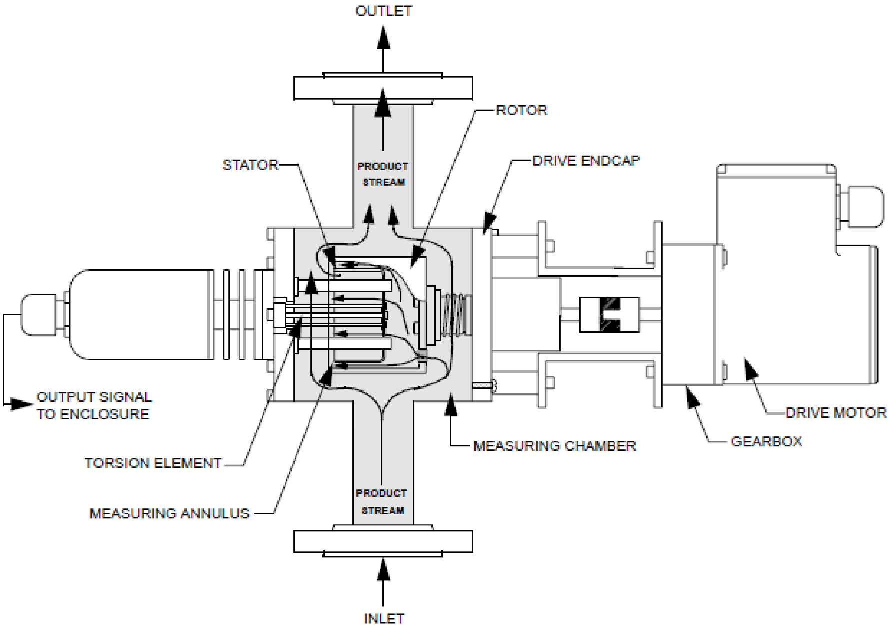


Figure 3-4 TT-100 viscometer [11]

3.2 Density sensor

Density can be measured in several ways; first there is the nuclear densometer. It uses a radioactive source to send radiation through the drilling fluid to a detector that is counting the number of photons received in a period. This is an accurate sensor but there are implications with nuclear sources on a drilling rig [14].

In all fairness, there is only one density sensor well suited for the mud sampling skid and that is a coriolis sensor. Even though its main purpose is to measure density, it also measures mass flow and the temperature of the fluid. Mass flow is used in the PLC program as a safety mechanic. Since the sampling pump set for a flow at five GPM, the coriolis verifies the flow and if the flow drops below a set point it indicates an error. The temperature is used in correlation to the viscosity measurment, viscosity readings are directly affected by the fluids temperature therefore stamping the readings with temperature is needed.

To describe how the coriolis measuring principle works, we have to take a step back and look at the Coriolis Effect that the measurement is based on.

The Coriolis effect is named after its discoverer, the French mathematician Gaspard-Gustave Coriolis. He set out the physical basic for the measuring principle for over 200 years ago.
The corilolis effect describes how an object behave in a rotation reference frame, the most common example is the earth rotation. When flying a straight line from Norway to the Canary Islands without taking in consideration the coriolis effect, the plane would end up in the Atlantic ocean. The mathematical formula for this fictitious force is shown in figure 3-5, where M is the objects mass, ω is the angular velocity and v the velocity of the object.

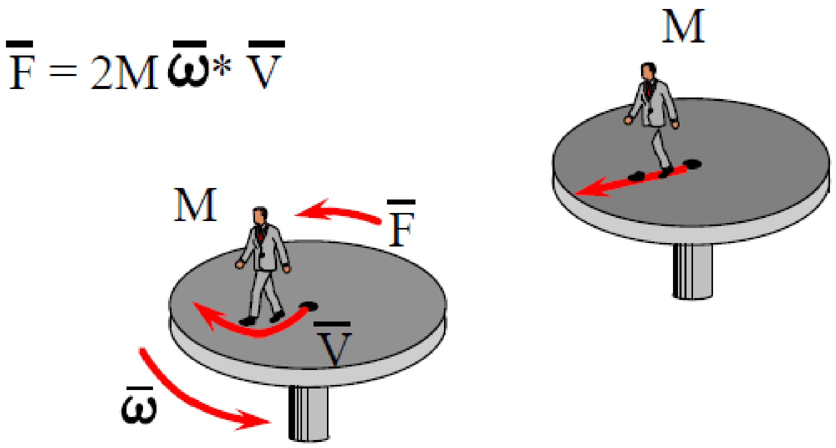


Figure 3-5 The coriolis force [15]

There are many different designs of coriolis instruments, but they all use the same technique. The principle is to oscillate perpendicular to its direction of movement. Two tubes are located inside each coriolis and are oscillated at a natural frequency by a drive coil and magnet. The coil keeps the system vibrating at its natural frequency. When mass flows in the tubes, the coriolis pickoffs measure the flow as a wave signal. When there is no flow in the coriolis sensors, the pick-up coils register that the signals on inlet and outlet side are identical. However, with flow in the tubes the pick-up coils detects a phase shift in the signal, this is the mass flow rate, as shown in figure 3-6. Mass flow can be converted into volumetric flow by dividing on the density.

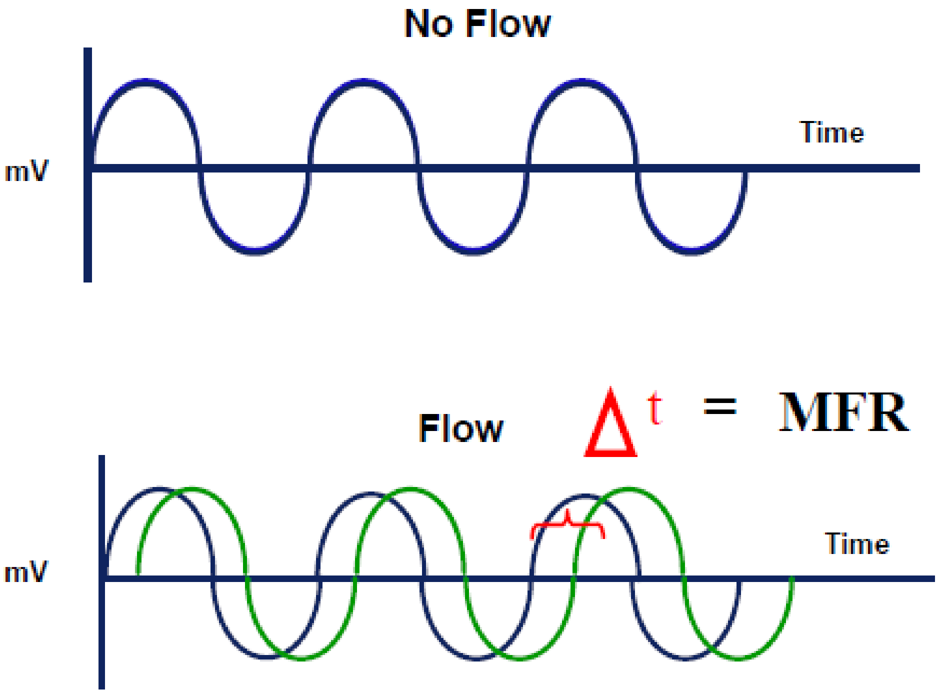


Figure 3-6 Coriolis mass flow [15]

The density measurement is based on the fluids natural frequency response. The instrument is oscillated with the same drive gain and measures the frequency response of the oscillation when fluid flows through the sensor. The instrument operates just like a mass spring system, at a high density the sensor registries a signal with a low frequency, as shown in figure 3-7.

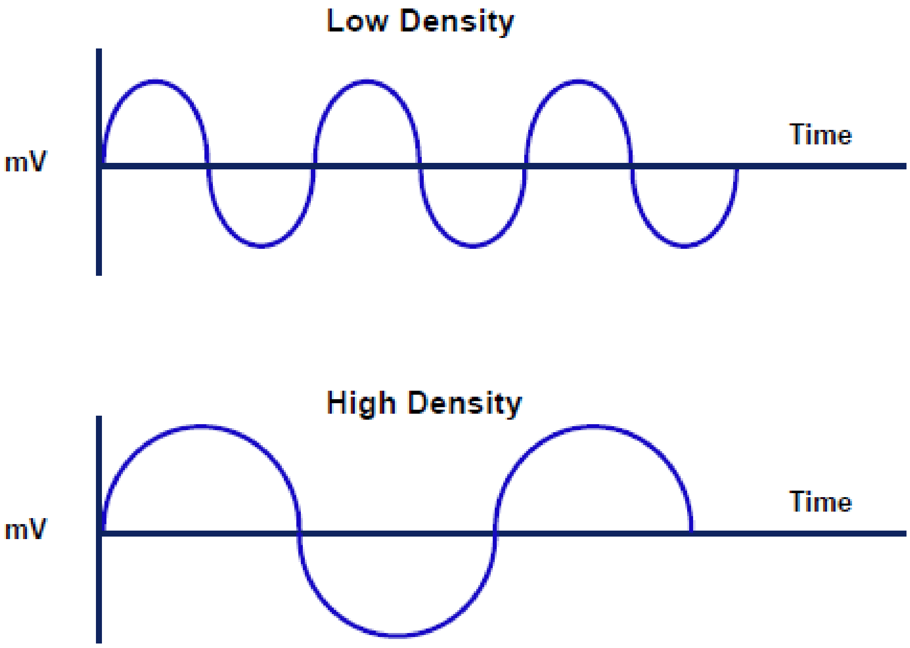


Figure 3-7 Density measurement [15]

4 PROGRAMMING

A standalone system that measure density and viscosity is nothing new in itself, but to integrated it as a part of a larger system is not been done before. The philosophy from an automation and signal processing background was immediately to look into how to make the system as smartly integrated as possible.

The first issue with a measuring on drilling fluid is the harshness of drilling fluid. The drilling fluid is a thixotropic shear thinning fluid, as described in 2.2, which means that whenever the fluid is in a stationary state the fluid stiffens up. This gives a challenge regarding maintenance of the thin sampling line that goes into the skid. Drilling fluid have a tendency to clog pipes if there no flow in the pipes for a longer periods. To prevent this for accruing to often I designed an automatic flushing system, will go in more details in the next chapter.

To be able to make a system automatic it needs to have feedback and monitoring from other sensors or components that is of interest for the system. When developing a system for a large company like NOV, I have the advantage of being able to use the existing signals from other system.

4.1 NOV Control System Topology

We can basically divide NOV's control system into three levels:

1. Cyberbase Control System is where the operator can control and monitor every integrated field unit in one system.
2. Machinery control is the PLC and I/O equipment for interfacing, controlling and automation tasks. This is the brain of the system.
3. Physical machinery and field instrumentations.

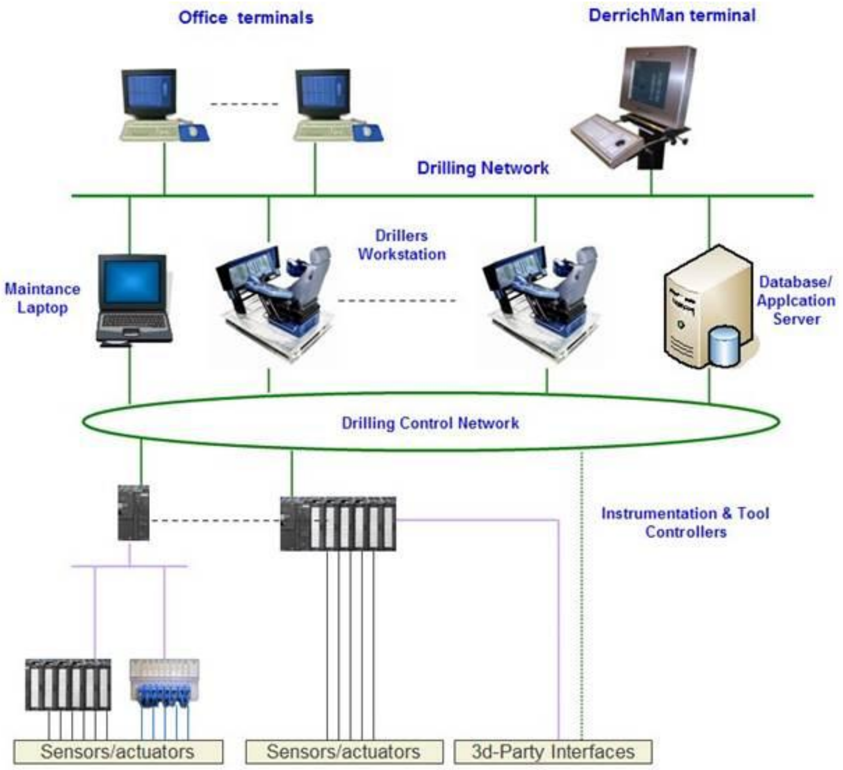


Figure 4-1 Control System Topology

The mud sampling system is involved in all three levels of this system. From the bottom of the chain, as the sensors feeds information to the PLCs and up to the HMI on either a cyberbase or a terminal.

When hooked up on the drilling control network, shown in figure 4-1, the mud sampling system have signals available from every sensor connected to the drilling control network.

4.2 Description of the system

The program for the mud sampling system was written in Siemens SIMATIC step 7, which is also used in the rest of the National Oilwell Varco's control systems.
The most common languages to program in step 7 are:

- Statement List, shortened to STL.
- Ladder Diagram, shortened to LAD.
- Function Block Diagram, shortened to FBD.

The setup for the sequence program is based on the S88 automation standard, witch was developed by multiple batch-manufacturing experts in the 1990's [8]. By following three main principles:

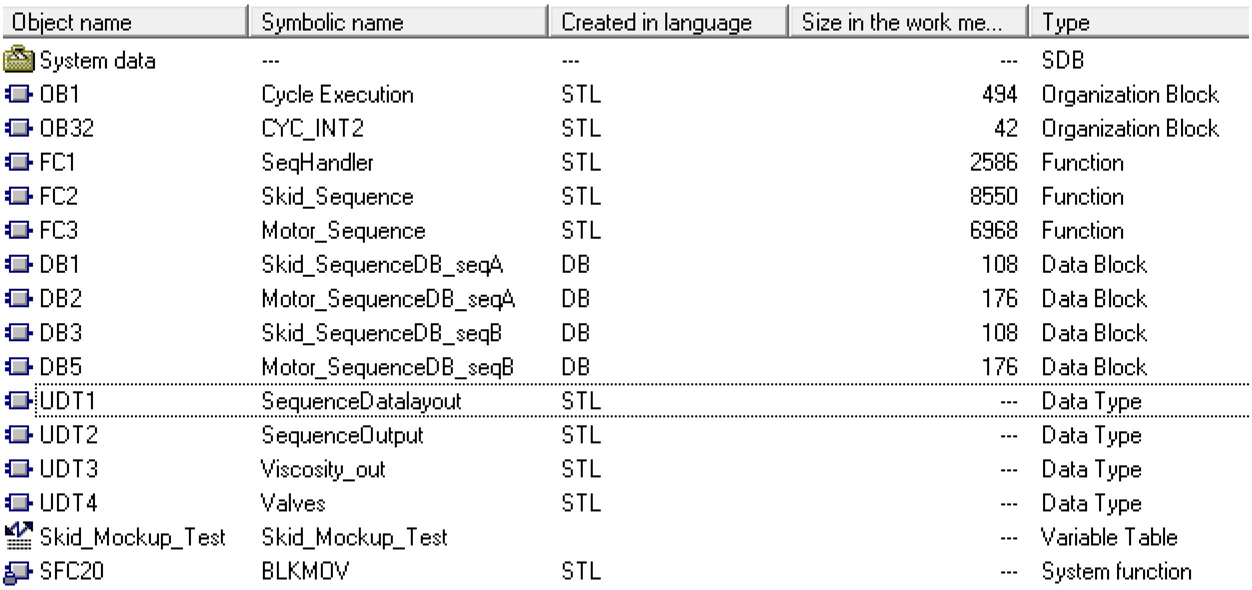
- The system should be modular sequenced, such as draining, measuring or flushing;
- The procedural steps should be programed independently of the equipment's or the action preformed;
- The logic of the equipment should be logged in a data file.

In the mud sampling system STL was used as the programing language, even though LAD and FBD are visual and easier to learn. Programming a program with two sequences running in parallel would be too complex for LAD and FBD, and therefore not suitable for this program.

The programs general sequential structure based on S88 are as following:

- **Sequence always executed code:** This is code is always executed no matter what state the sequences are in. It is used for the global change condition for entering a pause state.
- **Jump table:** At each scan, the program checks where to jump according to the "ActState" parameter. This parameter is set according to what state the program is currently in, and change in condition.
- **States:** The system is divided into several steps so called states. The program executes the states in a given order and can only be in one state at a time. In the mud sampling system there is nine states for the main program and seven for the slave program. The layout is as following:
    - The first step is to check if this is the first cycle scan after a change in state;
    - The state is then saved as the current restart state. It is used to return to the state if there is a pause from the global change condition;
    - Output component bits are set. Such as valves or sampling pump;
    - One scan code: This is where codes that are only activated when entering a scan is put. Like activating a timer or saving a measuring value.
    - Change condition: This is the criteria for changing a state. Definitions:

- There are no limitations to how many conditions a state can have. Every change condition can be considered as an OR function of its earlier condition;
- One can jump to any state in the program, as long as the state is included in the jump table;
- One can use any logical expression in a change condition;
- It is smart to make a layout of the change condition before programming.



Object name	Symbolic name	Created in language	Size in the work me...	Type
System data	---	---	---	SDB
OB1	Cycle Execution	STL	494	Organization Block
OB32	CYC_INT2	STL	42	Organization Block
FC1	SeqHandler	STL	2586	Function
FC2	Skid_Sequence	STL	8550	Function
FC3	Motor_Sequence	STL	6968	Function
DB1	Skid_SequenceDB_seqA	DB	108	Data Block
DB2	Motor_SequenceDB_seqA	DB	176	Data Block
DB3	Skid_SequenceDB_seqB	DB	108	Data Block
DB5	Motor_SequenceDB_seqB	DB	176	Data Block
UDT1	SequenceDatalayout	STL	---	Data Type
UDT2	SequenceOutput	STL	---	Data Type
UDT3	Viscosity_out	STL	---	Data Type
UDT4	Valves	STL	---	Data Type
Skid_Mockup_Test	Skid_Mockup_Test		---	Variable Table
SFC20	BLKMOV	STL	---	System function

Figure 4-2 Program overview

The mud sampling system consists of two identical physical measuring lines. As described in chapter 3, they both consist of the same amount valves, pumps and sensors. When programming you want to make the program as efficient and clean as possible. In the mud sampling system this is achieved by making a pair of function (FC2 and FC3), and running them in parallel. This simplifies the program and it requires less memory, as shown in figure 4-2.

Figure 4-2 shows a list of inventory in the mud sampling system program, it lists up all the files that are included in the program starting with OB1. OB stands for organization block and is in Siemens S7 OB1 pre-defined as the main program block. OB1 runs continually in each scan and is directing the program where to go and when. OB32 is an interrupt block that interrupts once in second, at every interrupt it subtracts one from the timer making it a counter.

The logic and control is conducted inside what is called a function call. The first function call is the FC1, it handle the overall steps of a sequence program and is called the sequence handler. It tells the program where to jump, setting active components and saving the three latest states of the program. This is a helpful function to keep track and debug the system.

The next function call is the FC2, this is where the mud sampling system sequence is programed. It consists of all the logic regarding handling and controlling of the automated system.

FC3 is the handling of the step-up function on the viscosity sensors motor. As described in 3.1, to simulate the flow profile the viscosity at six different shear rates are required in drilling operation. It then calculates the viscosity for every shear rate and the plastic viscosity and yield point.

Data blocks are storing information for either further mapping to HMI or internal storage. To run FC2 and FC3 for each line, the information from each line needs to be stored in separable set of data blocks. DB1 and DB2 are storing data from the return line, while DB3 and DB5 from in to the well line. This is all made possible by using user defined data types (UDT) inside the FC's, this is called a subroutine. When calling the FC's in OB1 the routing to the specific DB's are defined, this makes it possible to run as many lines measuring lines as the user wants.

4.3 Main Sequence

The main sequence is the overall control of the mud sampling system. It controls the conditions to move the program from state to state and is programed in function call two.

4.3.1 Main sequence matrix

The sequence matrix is an overall view of witch component that is activated in given states.

Output components:	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6	Comp7
	Mud valve in	Water butterfly valve	Water ball valve	Mud valve out	Drain valve	Pump	Alarm Bit: Internal Flow Error
Step:							
0							
1							
10							
20							
25	x				x		
30	x				x	x	
35	x			x			
40	x			x		x	
50	x			x			
60	x			x			x
65		x	x		x		
70		x	x		x	x	
99							

Figure 4-2 Main sequence matrix

4.3.2 Global change conditions (Sequence paused)

The global change condition state is a safety state significant to all other states, and is a check that is done at every scan in the program. It checks for any components in alarm or in manual mode. If an error occurs to a component, the program will jump immediately into this state and the operator will receive a message on the HMI display. If the operator needs to immediately stop/pause running the system, pressing the pause-button will trigger program to the sequence state.

If the operator presses the stop-button in measuring mode or awaiting flow, the program will not stop immediately. The program will interpret the action as a stop for a longer period of time, therefore flushing the system before jumping to idle. The benefit of using the pause-button is that it gives the operator the opportunity to instantly stop the program. By using the restart-button the program will continue from the state where it was paused.

Active in steps	IF actual state >=20 and < 99	
Change condition:	**Jump to**	**Trigger**
	99	Components in alarm
	99	Components in manual
	99	Operator pressed paused

4.3.3 State 0 (Maintenance)

When starting up the program this is the first step in the sequence.
The purpose for this state is to have the ability to stay in a safe state for manual override the valves for maintenance purpose. This state makes it possible to manually close off parts of the line when doing maintenance of components. To enter and exit this state there is a service button on the HMI.

Active components:	None active components.	
One scan code:	No timers.	
Continuous in scan:	None.	
Change condition:	**Jump to**	**Trigger**
	1	Activate service off button

4.3.4 State 1 (Idle)

In the state of idle, the system is waiting for the operator to go into operation by pushing the start button or go to maintenance by pushing the service button. It is in this state the system returns to when the stop button is pushed during operation.

<table>
<tr><td>Active components:</td><td colspan="2">None</td></tr>
<tr><td>One scan code:</td><td colspan="2">None</td></tr>
<tr><td rowspan="3">Change condition:</td><td>Jump to</td><td>Trigger</td></tr>
<tr><td>0</td><td>Service ON button activated</td></tr>
<tr><td>10</td><td>Start button activated</td></tr>
</table>

4.3.5 State 10 (Preparation)

This state is one of the safety states the program needs to go through before it is allowed to start the measuring process. It is a logical check to see if any components are still in manual mode after perhaps exiting maintenance, or if there is any components error. If there is an error or components are in manual mode the operator will get a message on the HMI. The message will contain information about why it is not moving into operation. The operator also have the option to stop and go back to idle by pushing the stop button.

<table>
<tr><td>Active components:</td><td colspan="2">None</td></tr>
<tr><td>One scan code:</td><td colspan="2">None</td></tr>
<tr><td rowspan="3">Change condition:</td><td>Jump to</td><td>Trigger</td></tr>
<tr><td>1</td><td>Stop Button Activated</td></tr>
<tr><td>20</td><td>IF no components error AND no components in manual</td></tr>
</table>

4.3.6 State 20 (Awaiting Mud flow)

After the internal hardware checks the program now conducts an external operation check. This is done by using the external sensors to check if the condition allows the program to go into operation. For the mud return line, the program checks if the mud return flow sensor is over a calibrated set point. For mud into the well line the program checks how much mud is pumped into the well. If the external mud flow is larger than the set point then the operation condition allows the measuring to start.

There is a process delay from the external from the external flow sensor, called mud return, to the mud sampling system. To eliminate dry-running the sampling pump caused by the process delay, there is calibrated a delay in the program. This delay is calibrated for the specific rig during commissioning. To verify the flow is actually over the set point and not just a short variation in flow, the waiting flow timer is refreshed in every scan as long as the flow is under the set point. When the flow is high and timer runs out, the system have mud available then the pump is turn on in the next state.

<table>
<tr><td>Active components:</td><td>None</td></tr>
<tr><td>One scan code:</td><td>Waiting flow timer = calibrated on commissioning. (ex. 45s)</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>1</td><td>Stop Button Activated</td></tr>
<tr><td>25</td><td>IF External Mud Flow > Expected set point</td></tr>
</table></td></tr>
</table>

4.3.7 State 25 (Checking valves to prepare for drain)

When the valves are changing position from open to close the system needs to know that the task is complete before entering the next state. In this state the Mud-in-valve and Drain-valve are opened, all other valves are closed. To verify that all valves are in correct position, a timer starts and will set the program to sequence pause if any errors occurs. The timer is calibrated during commissioning according to the valves close and open time.

Active components:	Comp1: Mud In Comp5: Drain	
One scan code:	Valve timer = calibrate on commission (Timer1, 30s in the program)	
Change condition:	**Jump to**	**Trigger**
	30	IF Mud valve open and Drain valve open THEN
	99	IF Timer = 0, there is an error with the valves

4.3.8 State 30 (Draining System)

Draining the system is vital for the Automated cleaning in place- system designed for the automated sampling system. After a longer period of stop the system will be flushed with rig water. When the system is going back to measuring-mode there is water left in the pipes that needs to be removed before measuring the mud. The water will be pressed out by the mud into the drain pits. Mud is an expensive fluid that is mixed and optimized for the drilling application and formation, so it is crucial to not let any water into the mud pits.

The most efficient way to do this is to measure the time it takes for the mud to reach the drain pit, this is done at the specific rig the system is operated on. When the timer runs out the system will go to measuring-mode.
Since the automated mud sampling system is equipped with a density sensor, this system gives us a new way of minimizing the amount of mud that runs out into the drain pits. The operator obviously doesn’t want any wastage of mud each time the system needs to be cleaned. The program saves the first measurement in density upon entering this state, this is water with a SG approximately equal to 1. The program subtracts the measured density in each scan, and calculates a delta density. When the delta density exceeds a set threshold value, it indicated drilling fluid in the pipes. To make sure all water is out of the piping there is programed a delay from the point of change in density accrues. This delay needs to be calibrated depending on the length of piping to drain pits.

<table>
<tr><td>Active components:</td><td colspan="2">• Comp1: Mud-In-valve
• Comp5: Drain-valve
• Comp6: Pump</td></tr>
<tr><td>One scan code:</td><td colspan="2">SeqTimer1 = [DrainTime] - (15 sek.)
SeqTimer2 = [MaxDrainTime] - (300 sek.)
Save First Density</td></tr>
<tr><td>Continuous in scan</td><td colspan="2">IF Coriolis Density Delta < [DeltaSPMudWater] THEN
   SeqTimer1 = [DrainTime]</td></tr>
<tr><td rowspan="3">Change condition:</td><td>Jump to</td><td>Trigger</td></tr>
<tr><td>35</td><td>After the timer1 = 0</td></tr>
<tr><td>35</td><td>After the timer2 = 0</td></tr>
</table>

4.3.9 State 35 (Checking valves to prepare for drain)

This state is preparing for measuring, and is therefore opening for mud in and mud out valves, and have same function as 4.3.7.

<table>
<tr><td>Active components:</td><td>• Comp1: Mud In
• Comp4: Mud out</td></tr>
<tr><td>One scan code:</td><td>Valve timer = 30s (Timer1)</td></tr>
<tr><td>Change condition:</td><td><table><tr><th>Jump to</th><th>Trigger</th></tr><tr><td>40</td><td>IF Mud valve open and Mud out valve open THEN</td></tr><tr><td>99</td><td>IF Timer = 0, there is an error with the valves</td></tr></table></td></tr>
</table>

4.3.10 State 40 (Measuring Viscosity and Density)

When entering the measuring state the sampling pump starts. This state triggers the slave sequence, which runs in parallel to start the TT-100 motor and the measuring will commence.

The first change condition is a check on the external flow sensor. If it gets lower than the setpoint, the system will set into a pause state. This will normally occur quite often since the external flow sensor will go low during tripping and tool connection.

The second change condition is an internal flow check. If the flow is lower than the setpoint and external flow is in operation, this can be caused by clogging or leakage in the piping, or an error in the pump. When entering this state the flow might not be in operational speed, this would trigger the internal flow check and send the system to idle with an error message. To eliminate this problem a proses delay timer was added. The delay gives the pump time to get up to operational rates before the internal change condition is valid.

The third method for exiting the measuring state is to press the stop button. Pushing the stop button indicates a longer period of stoppage time. The system will then remember it was stopped by pushing the stop button, and automatically go into idle after the mud sampling skid is flushed. Since the operator did not turn off the program, the program returns to awaiting mud flow, state 20, where it can go back into measuring when conditions allows it.

<table>
<tr><td>Active components:</td><td>• Comp1: Mud In
• Comp4: Mud Out
• Comp6: Pump</td></tr>
<tr><td>One scan code:</td><td>Process delay timer = 60s</td></tr>
<tr><td>Change condition:</td><td>
<table>
<tr><th>Jump to</th><th>Trigger</th><th>Activity on change</th></tr>
<tr><td>50</td><td colspan="2">IF ExtFlowSensor < [ExtFlowParameter]</td></tr>
<tr><td>60</td><td colspan="2">IF IntCoriolisFlow < [IntFlowParameter]</td></tr>
<tr><td>65</td><td>IF Stop Button is pushed</td><td>[PostNext] = 1</td></tr>
</table>
</td></tr>
</table>

4.3.11 State 50 (Measuring Pause)

This is the controlled stop state. A stop in circulation which triggers the external flow, will make the program jump into the measuring pause state. The program will consider whether it is just a short pause or a stop that requires flushing. A pause in circulation will occur while changing of the drilling bit or adding tools, and when adding length to the string. This will happen quite often during the drilling operation. To prevent the system too instantly going into flushing at every stop, this state will diagnose if it a short pause or an actual stop.

This is done by checking if external flow is higher than the setpoint. If this occurs, the system jumps back to the measuring state and continues to measure. If the external flow does not go higher than the setpoint within 30 minutes, the system concludes that this is an actual stop and flushing starts. The program will remember where to go after flushing, depending of what change condition triggered the flushing. If the flushing was caused by time running out, the program will jump into a waiting mud flow state. If the flushing was caused by the operator pressing the stop-button, the program will go to idle.

<table>
<tr><td>Active components:</td><td>• Comp1: Mud-in-valve
• Comp4: Mud-Out-valve</td></tr>
<tr><td>One scan code:</td><td>Timer = 1800s, SeqTimer1 (30min)</td></tr>
<tr><td>Change condition:</td><td>
<table>
<tr><th>Jump to</th><th colspan="2">Trigger</th></tr>
<tr><td>40</td><td colspan="2">IF ExtFlowSensor > [ExtFlowParameter]</td></tr>
<tr><td>65</td><td>Timer = 0</td><td>[PostNext] = 20</td></tr>
<tr><td>65</td><td>IF Stop Button is pushed</td><td>[PostNext] = 1</td></tr>
</table>
</td></tr>
</table>

4.3.12 State 60 (Internal Error)

Upon entering the internal error state the internal flow has been lower than the setpoint for a period of time. This indicates either leakage in the piping, clogging or an error in the coriolis sensor. A pop-up message occurs on the HMI, giving information to the operator about why the measuring has been stopped, and recommends conducting maintenance on the mud sampling system.

The program then jumps into flushing, to make the system free from mud when maintenance is done.

<table>
<tr><td>Active components:</td><td colspan="3">Comp7. (Alarm internal flow error)</td></tr>
<tr><td>One scan code:</td><td colspan="3">No</td></tr>
<tr><td rowspan="2">Change condition:</td><td>Jump to</td><td>Trigger</td><td>Activity on change</td></tr>
<tr><td>65</td><td>Unconditional</td><td>[PostNext] = 1</td></tr>
</table>

4.3.13 State 65 (Checking valves to prepare for flush)

This state is preparing the valves for flushing, and making sure that the valves are in right position before entering the next state.

<table>
<tr><td>Active components:</td><td colspan="2">• Comp2: Water butterfly
• Comp3: Water ball
• Comp5: Drain</td></tr>
<tr><td>One scan code:</td><td colspan="2">Valve timer = 30s (Timer1)</td></tr>
<tr><td rowspan="3">Change condition:</td><td>Jump to</td><td>Trigger</td></tr>
<tr><td>40</td><td>IF Water butterfly AND Water ball AND Drain is OPEN THEN GO</td></tr>
<tr><td>99</td><td>IF Timer = 0, there is an error with the valves</td></tr>
</table>

4.3.14 State 70 (Flush)

Working with any equipment in contact with drilling fluid requires substantial amount of maintenance. With all the different chemicals added to the drilling fluid, the fluid is harsh to any materials it is in contact with.
To extend the mud sampling systems life span, an automated flushing system is absolutely crucial. This system cannot completely remove the need for manually maintenance but it will reduce the frequency of the need of manual labor substantially.

Whenever the system is going from a state with drilling fluid in the pipes to stop for longer period of time, the pipes and sensors will be flushed. The drilling fluid is a shear thinning with thixotropy properties, turns into jelly substance and thickens up under static conditions. With sensitive sensors like the TT-100 with small narrow gaps and moving parts, it is absolutely necessary to keep it as clean as possible when not in use.

When the valves are opened for flushing the pump starts pumping in fresh water from the rig , through the system and into the drain. When flushing, the motor in the TT-100 sensor starts rotating with a steady speed to get the inside of the sensor as clean as possible. This is done in 8 minutes before the system goes on into the next predestine state based on earlier conditions.

<table>
<tr><td>Active components:</td><td>• Comp2: Water Butterfly
• Comp3: Water Ball
• Comp5: Drain
• Comp6: Pump</td></tr>
<tr><td>One scan code:</td><td>SeqTimer1 = [Flushtime] - 480s, (8 min)</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>1</td><td>IF Timer = 0 AND [PostNext] = 1</td></tr>
<tr><td>20</td><td>IF Timer = 0 AND [PostNext] = 20</td></tr>
</table></td></tr>
</table>

4.3.15 Master sequence flow diagram

The chapters above have given a detailed step by step explanation of each of the states in the master sequence. The flow diagram in figure 4-4 below, summarize the system described the chapters for each state. This gives a more visual overview of the interconnection of the program.

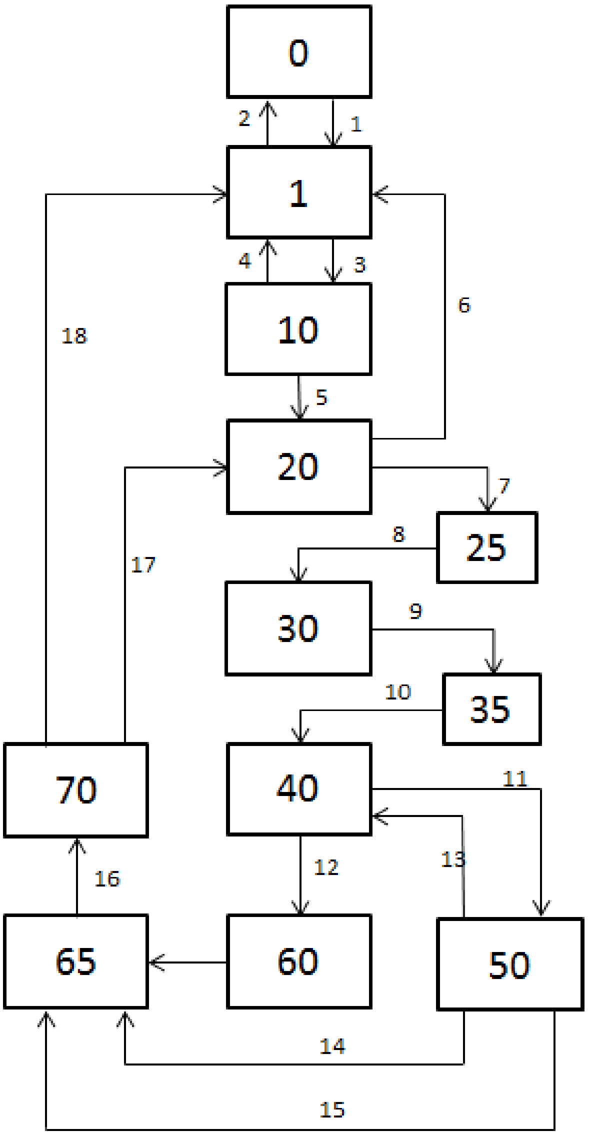


Figure 4-3 Master sequence flow diagram

The numbers between the boxes in the flow diagram are the different change conditions in the program. The numbers in figure 4-4 refers to these numbers:

1. Service button off pushed
2. Service button on pushed
3. Start button on pushed
4. Stop button on pushed

5. No components error AND no components in manual
6. Stop button pushed
7. External Mud Flow > Expected setpoint
8. Valves in position
9. Delta density > delta density setpoint OR max drain timer
10. Valves in position
11. External flow sensor < external flow setpoint
12. Internal flow sensor < internal flow setpoint
13. External flow sensor > external flow setpoint
14. Maximum pause timer
15. Stop button pushed
16. Valves in position
17. Finished flushing and next position = 20
18. Finished flushing and next position = 1

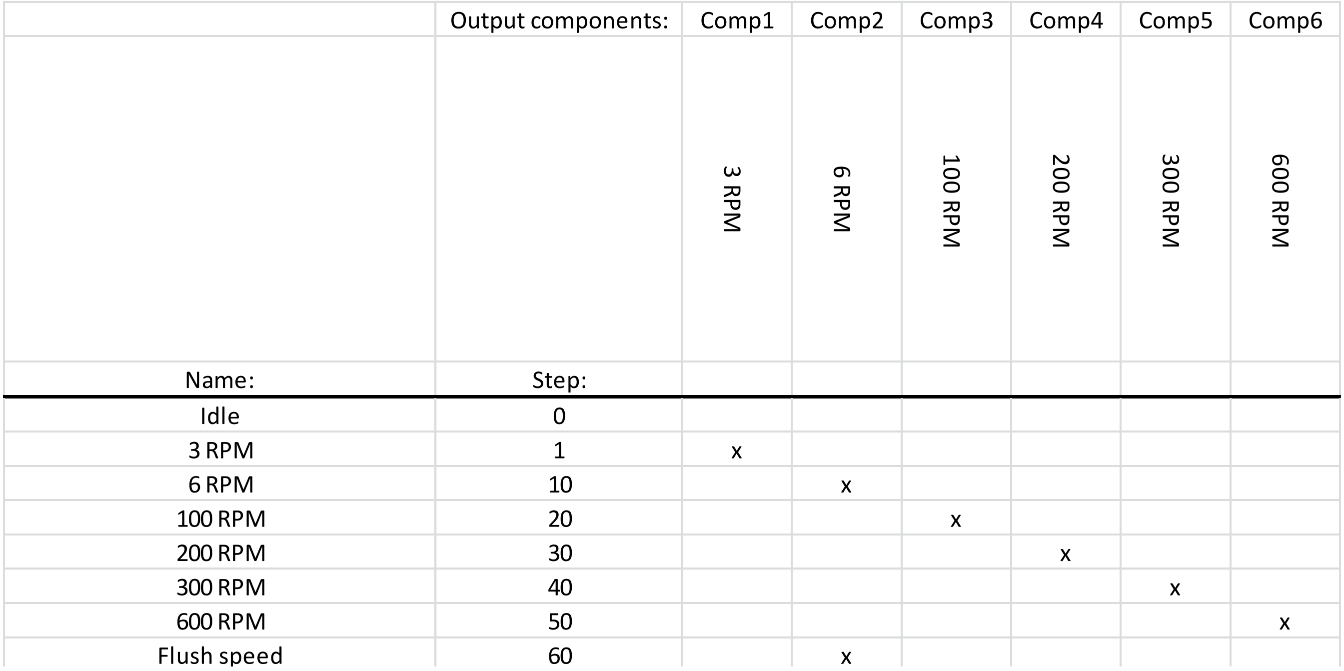
4.4 Slave Sequence

The slave sequence is the program that runs the function for measuring of the different shear rates for the viscosity. It runs in parallel with the main sequence and is programmed in FC3. The reason for measuring the viscosity in six different shear rates is because of the drilling fluids non-Newtonian properties.

The task for the slave sequence is to run the TT-100 stepper motor and calculate the viscosity.

4.4.1 Slave sequence matrix

The sequence matrix is an overview of what speed is activated in given states.



	Output components:	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
		3 RPM	6 RPM	100 RPM	200 RPM	300 RPM	600 RPM
Name:	Step:						
Idle	0						
3 RPM	1	x					
6 RPM	10		x				
100 RPM	20			x			
200 RPM	30				x		
300 RPM	40					x	
600 RPM	50						x
Flush speed	60		x				

Figure 4-5 Slave sequence matrix

4.4.2 State 0 (Idle)

In this state the program is waiting for the master sequence actual state to go into measuring mode, state 40. It is continually running in parallel with the main sequence and imports the main programs actual state.

<table>
<tr><td>Active components:</td><td>None</td></tr>
<tr><td>One scan code:</td><td>None</td></tr>
<tr><td>Continuous in scan:</td><td>Nothing</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>1</td><td>IF master Actual State is 40, measuring mode.</td></tr>
<tr><td>60</td><td>IF master actual state is 70, flush.</td></tr>
</table></td></tr>
</table>

4.4.3 State 1 (Shear rate: 5 (3 RPM))

This is the first of six states of measuring the viscosity at a set shear rate. Upon entering this state the viscometers motor starts rotating equivalent to 5s$^{-1,}$ and starts measuring the torque induced by the drilling fluid on the sensor. The speed and viscosity range is saved for the set shear rate and is used in the calculation for viscosity at given shear rate.
The torque value is then converted into viscosity in centipoise as described in chapter 3.1.

The measuring process is executed in two minutes before it moves on to the next shear rate.

<table>
<tr><td>Active components:</td><td>Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td>Sets SeqTimer1 = 120s</td></tr>
<tr><td>Continuous in scan:</td><td>Calculation Viscosity at 5 shear rate.</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>10</td><td>WHEN SeqTimer1 = 0, then jump to 10</td></tr>
<tr><td>0</td><td>IF master actual state <> 40, then jump to 0</td></tr>
</table></td></tr>
</table>

4.4.4 State 10 (Shear rate: 10 (6 RPM))

Measuring viscosity just like in state 1 but now using shear rate at $10s^{-1}$ for two minutes, before moving on to the next shear rate.

<table>
<tr><td>Active components:</td><td colspan="2">Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td colspan="2">Sets SeqTimer1 = 120s</td></tr>
<tr><td>Continuous in scan:</td><td colspan="2">Calculation Viscosity at 10 shear rate.</td></tr>
<tr><td rowspan="3">Change condition:</td><td>Jump to</td><td>Trigger</td></tr>
<tr><td>20</td><td>WHEN SeqTimer1 = 0, the jump to 20</td></tr>
<tr><td>0</td><td>IF master actual state <> 40, then jump to 0</td></tr>
</table>

4.4.5 State 20 (Shear rate: 170 (100 RPM))

Measuring viscosity just like in state 1 but now using shear rate at $170s^{-1}$ for two minutes, before moving on to the next shear rate.

<table>
<tr><td>Active components:</td><td colspan="2">Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td colspan="2">Sets SeqTimer1 = 120s</td></tr>
<tr><td>Continuous in scan:</td><td colspan="2">Calculation Viscosity at 170 shear rate.</td></tr>
<tr><td rowspan="3">Change condition:</td><td>Jump to</td><td>Trigger</td></tr>
<tr><td>30</td><td>WHEN SeqTimer1 = 0, the jump to 30</td></tr>
<tr><td>0</td><td>IF master actual state <> 40, then jump to 0</td></tr>
</table>

4.4.6 State 30 (Shear rate: 341 (200 RPM))

Measuring viscosity just like in state 1 but now using shear rate at 341s^{-1} for two minutes, before moving on to the next shear rate.

<table>
<tr><td>Active components:</td><td>Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td>Sets SeqTimer1 = 120s</td></tr>
<tr><td>Continuous in scan:</td><td>Calculation Viscosity at 341 shear rate.</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>40</td><td>WHEN SeqTimer1 = 0, the jump to 40</td></tr>
<tr><td>0</td><td>IF master actual state <> 40, then jump to 1</td></tr>
</table></td></tr>
</table>

4.4.7 State 40 (Shear rate: 511 (300 RPM))

Measuring viscosity just like in state 1 but now using shear rate at 511s^{-1} for two minutes, before moving on to the next shear rate.

<table>
<tr><td>Active components:</td><td>Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td>Sets SeqTimer1 = 120s</td></tr>
<tr><td>Continuous in scan:</td><td>Calculation Viscosity at 511 shear rate.</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>50</td><td>WHEN SeqTimer1 = 0, the jump to 50</td></tr>
<tr><td>0</td><td>IF master actual state <> 40, then jump to 1</td></tr>
</table></td></tr>
</table>

4.4.8 State 50 (Shear rate: 1022 (600 RPM))

The last state in the measuring cycle is measuring viscosity just as the other measuring state but at 1022s^{-1} shear rate. When completed a cycle scan, calculation of plastic viscosity and yield point is calculated as following:

$$PV = Theta_{600} - Theta_{300}$$

$$YP = Theta_{300} - PV$$

<table>
<tr><td>Active components:</td><td>Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td>Sets SeqTimer1 = 120s</td></tr>
<tr><td>Continuous in scan:</td><td>Calculation Viscosity at 1022 shear rate.</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>1</td><td>WHEN SeqTimer1 = 0, the jump to 1</td></tr>
<tr><td>0</td><td>IF master actual state <> 40, then jump to 1</td></tr>
</table></td></tr>
</table>

4.4.9 State 60 (Flush the chamber speed)

To make sure the viscometer is properly cleaned inside the stator and rotor, the motor rotates with a steady speed while flushing the system.

<table>
<tr><td>Description:</td><td>Gives the TT-100 motor a frequency matching 10 RPM</td></tr>
<tr><td>Active components:</td><td>Comp1: TT-100 Motor</td></tr>
<tr><td>One scan code:</td><td>None</td></tr>
<tr><td>Continuous in scan:</td><td>None</td></tr>
<tr><td>Change condition:</td><td><table>
<tr><th>Jump to</th><th>Trigger</th></tr>
<tr><td>0</td><td>IF master actual state is NOT 70.</td></tr>
</table></td></tr>
</table>

4.4.10 Slave sequence flow diagram

This is the flow diagram for the slave sequence program, the number inside the box is symbolizing each state. The names of each state correspond with the states in the chapters above.

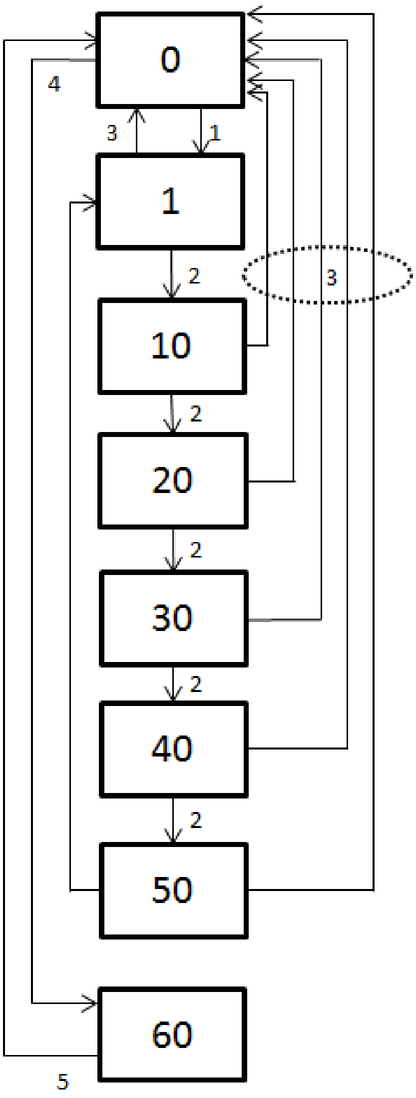


Figure 4-6 Slave sequence flow diagram

The numbers between the boxes in the flow diagram are the different change conditions in the program. The numbers in figure 4-4 refers to these numbers:

1. Master actual state = 40
2. Measuring timer = 2min
3. Master actual state ≠ 40
4. Master actual state = 70
5. Master actual state ≠70

5 DISCUSSION AND CONCLUSION

In this theses my main goal has been to look into the possibility to develop a system for measuring viscosity and density which are the main properties concerning drilling fluid. By monitoring the properties of the drilling fluid, the operator gets an indication on what is actually happening down in the well.

In the developing-phase of this thesis some new issues occurred which I had to take into consideration, such as manually or automatic flushing system. After researching the implication caused by drilling fluid on measurement equipment, I decided that an automated flushing system was crucial for increasing the life span of the system. By making the system less dependent on manually maintenance, it will have an economical benefit as well as reducing the risk of human error.

In the following I will highlight what I consider as benefits by developing this new system;

- Firstly: The first key advantage is the automatic flushing system. Without this feature I would consider it a higher risk of clogging, by being dependent on manually labor.
- Secondly: Implementation of the check in change of density while draining the system, results in minimizing drilling fluid going to waist. As drilling fluid is costly and can be a hazard for the environment, reducing drilling fluid going to waste is crucial.
- Thirdly: By using NOV’s existing flow sensors, this leads to an efficient use of the system. The system is able to adapt to the operation by stopping the system when it’s not necessary to conduct the measurement. This saves wear on the instruments and is beneficial from an economic view.
- Fourthly: When using a coriolis sensor for the measurement of density, the system also measures two more fluid parameters as mass flow and temperature. Information of temperature is absolutely needed as it’s directly correlated to the viscosity reading. When displaying a viscosity reading on the HMI the temperature is stamped to the measurement. The mass flow is used as an internal diagnostic of the system. If the rig is in operation and the internal flow drops below the pump speed, it indicates a problem in the system.

As this system is not yet field tested I have some concerns that are worth considering. The first Component with an uncertain element is the sampling pump. Because of the limitation of 0,7 bar suction pressure, the position of the pump is limited. I find it also necessary to point out that the life span of the pump needs to be taken under consideration. After consulting with the supplier, they made me aware of the life span can vary from six month to a couple of years.

Either hardware or software has been properly field tested. The software which I have developed has been simulated and verified in the Siemens simulation program. The hardware is now under construction and the full scale test will be conducted in the following months. I consider my task in developing a preliminary design for an automated measurement system as fulfilled, but it remains to be seen how this will work in reality. I will have the pleasure of continue working with the system in the future, and I expect the opportunity will arise to develop the product further on.

Reference list

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[2] H. C. H. Darley; George R. Gray (1988) “Composition and Properties of Drilling and Completion Fluids” Fifth Edition

[3] Faith A. Morrison (2013) “An introduction to fluid mechanics” First Edition

[4] R.P. King (2002) “Introduction to practical fluid flow” First Edition

[5] http://www.drillingcontractor.org/ Drilling fluid circulation system figure, with MSS added.

[6] “14-P-220 Triplex Mud Pump Data Sheet” by National Oilwell Varco

[7] Pål Skalle(2013) “Drilling Fluid Engineering”

[8] “The ISA S88 Standard – A Roadmap for Automation – A Powerful Management Tool” by Rockwll Automation.

[9] http://en.wikipedia.org/wiki/Non-Newtonian_fluid

[10] Fann Equivalent data sheet form Brookfield engineering

[11] Brookfield TT-100 instrument manual

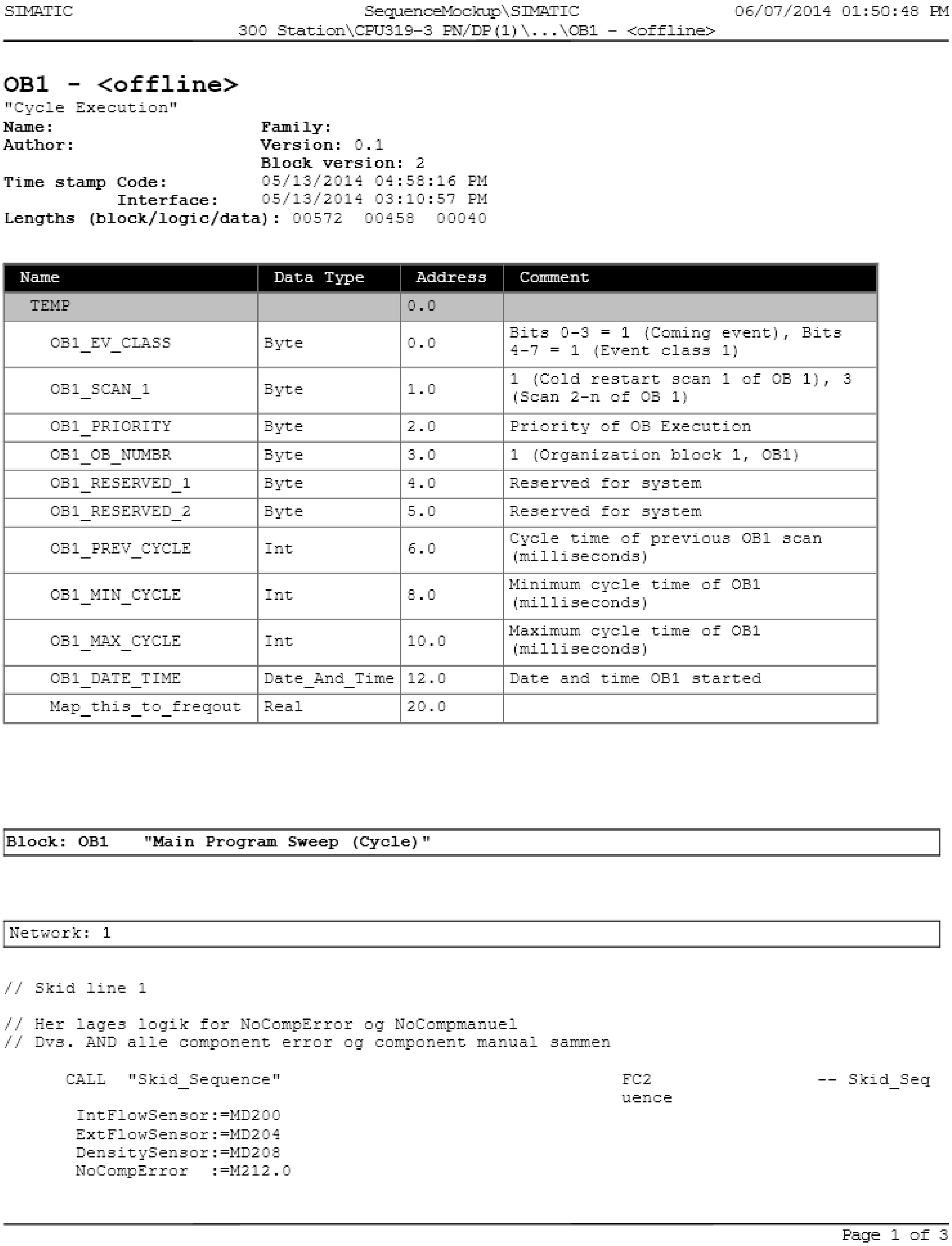
[12] Howard A. Barnes (2000) “A handbook of elementart rheology” first Edition

[13] Drawn by Watech AS, designed by myself incorporation with NOV.

[14] http://en.wikipedia.org/wiki/Nuclear_densometer

[15]Presentation from Emerson about coriolis by Laura Schafer

Appendix A – OB1 execution of the program



SIMATIC SequenceMockup\SIMATIC 300 Station\CPU319-3 PN/DP(1)\...\OB1 - <offline> 06/07/2014 01:50:48 PM

OB1 - <offline>

```
"Cycle Execution"
Name:                   Family:
Author:                 Version: 0.1
                        Block version: 2
Time stamp Code:        05/13/2014 04:58:16 PM
           Interface:   05/13/2014 03:10:57 PM
Lengths (block/logic/data): 00572  00458  00040
```

Name	Data Type	Address	Comment
TEMP		0.0	
OB1_EV_CLASS	Byte	0.0	Bits 0-3 = 1 (Coming event), Bits 4-7 = 1 (Event class 1)
OB1_SCAN_1	Byte	1.0	1 (Cold restart scan 1 of OB 1), 3 (Scan 2-n of OB 1)
OB1_PRIORITY	Byte	2.0	Priority of OB Execution
OB1_OB_NUMBR	Byte	3.0	1 (Organization block 1, OB1)
OB1_RESERVED_1	Byte	4.0	Reserved for system
OB1_RESERVED_2	Byte	5.0	Reserved for system
OB1_PREV_CYCLE	Int	6.0	Cycle time of previous OB1 scan (milliseconds)
OB1_MIN_CYCLE	Int	8.0	Minimum cycle time of OB1 (milliseconds)
OB1_MAX_CYCLE	Int	10.0	Maximum cycle time of OB1 (milliseconds)
OB1_DATE_TIME	Date_And_Time	12.0	Date and time OB1 started
Map_this_to_freqout	Real	20.0	

Block: OB1 "Main Program Sweep (Cycle)"

Network: 1

```
// Skid line 1

// Her lages logik for NoCompError og NoCompmanuel
// Dvs. AND alle component error og component manual sammen

      CALL  "Skid_Sequence"                           FC2               -- Skid_Seq
                                                      uence
       IntFlowSensor:=MD200
       ExtFlowSensor:=MD204
       DensitySensor:=MD208
       NoCompError  :=M212.0
```

Page 1 of 3

```
       NoCompManual :=M212.1
       seq          :="Skid_SequenceDB_seqA".Seq          P#DB1.DBX0.0        -- Sequence
                                                          data
       Valves       :="Skid_SequenceDB_seqA".Valves       P#DB1.DBX70.0       -- Valves f
                                                          or each line

// Call seqeunce handler for skid sequence line 1
      CALL  "SeqHandler"                                  FC1                 -- Sequence
                                                           Handler
       Seq:="Skid_SequenceDB_seqA".Seq                    P#DB1.DBX0.0        -- Sequence
                                                          data


// Her mappes output til motor/ventil handlerens program output


// Call Motor sequence line 1
      CALL  "Motor_Sequence"                              FC3
       MasterActState:="Skid_SequenceDB_seqA".Seq.ActState DB1.DBW4           -- Actual s
                                                          tate for sequence
       Freq_speed    :=#Map_this_to_freqout               #Map_this_to_freqout
       Seq           :="Motor_SequenceDB_seqA".Seq        P#DB2.DBX0.0        -- Sequence
                                                          data
       Viscosity     :="Motor_SequenceDB_seqA".Viscosity  P#DB2.DBX70.0


// Call seqeunce handler for motor speed line 1
      CALL  "SeqHandler"                                  FC1                 -- Sequence
                                                           Handler
       Seq:="Motor_SequenceDB_seqA".Seq                   P#DB2.DBX0.0        -- Sequence
                                                          data


// Her mappes output til motor/ventil handlerens program output


// Skid linie 2
// Her lages logik for NoCompError og NoCompmanuel
// Dvs. AND alle component error og component manual sammen

      CALL  "Skid_Sequence"                               FC2                 -- Skid_Seq
                                                          uence
       IntFlowSensor:=MD300
       ExtFlowSensor:=MD304
       DensitySensor:=MD308
       NoCompError  :=M312.0
       NoCompManual :=M312.1
       seq          :="Skid_SequenceDB_seqB".Seq          P#DB3.DBX0.0        -- Sequence
                                                          data
       Valves       :="Skid_SequenceDB_seqB".Valves       P#DB3.DBX70.0       -- Valves f
                                                          or each line

// Call seqeunce handler for master sequence line 2
      CALL  "SeqHandler"                                  FC1                 -- Sequence
                                                           Handler
       Seq:="Skid_SequenceDB_seqB".Seq                    P#DB3.DBX0.0        -- Sequence
                                                          data

// Call Motor sequence linje 2
      CALL  "Motor_Sequence"                              FC3
```

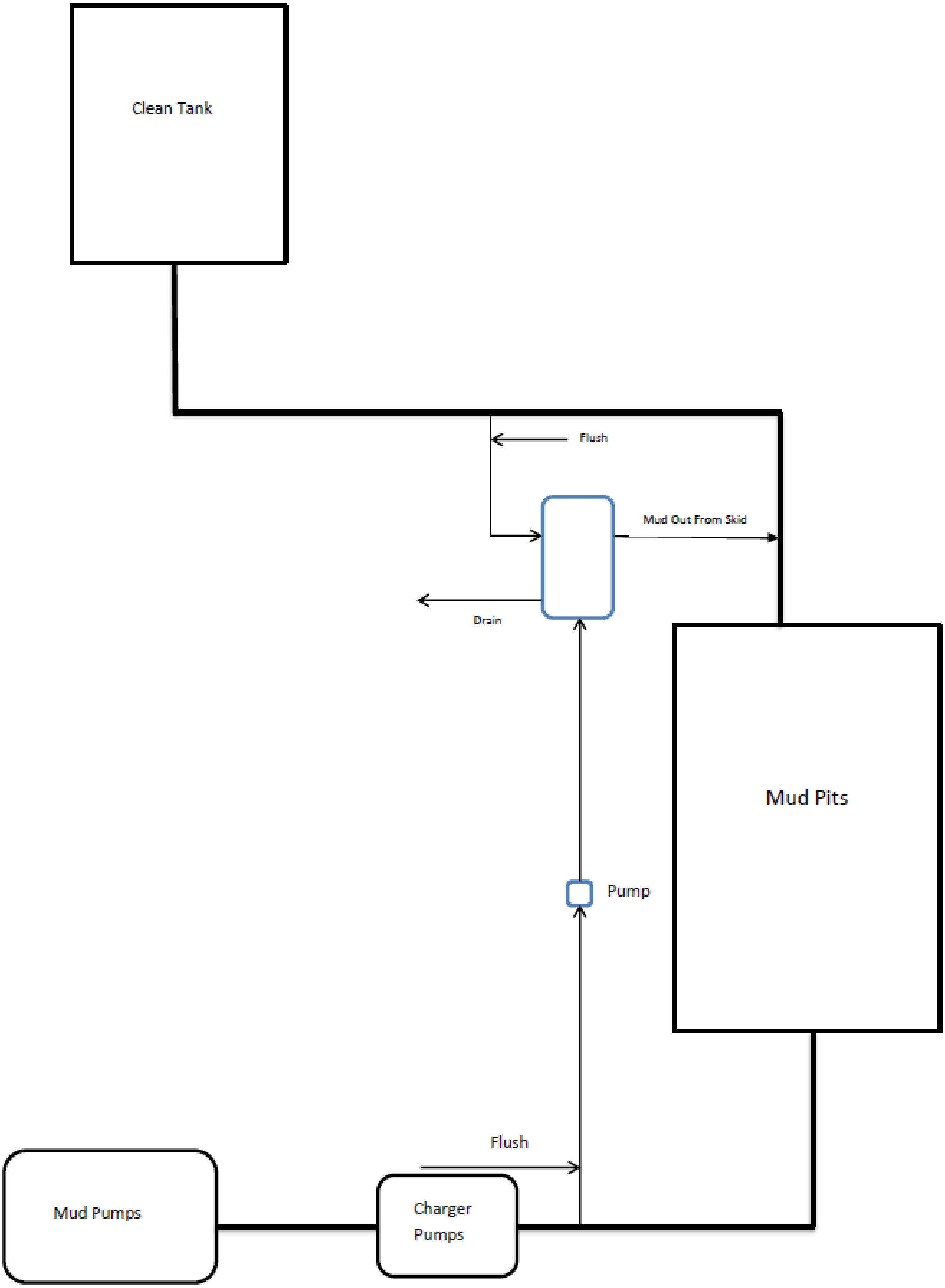
```
       MasterActState:="Skid_SequenceDB_seqB".Seq.ActState  DB3.DBW4            -- Actual s
                                                            tate for sequence
       Freq_speed    :=#Map_this_to_freqout                 #Map_this_to_freqout
       Seq           :="Motor_SequenceDB_seqB".Seq          P#DB5.DBX0.0        -- Sequence
                                                            data
       Viscosity     :="Motor_SequenceDB_seqB".Viscosity    P#DB5.DBX70.0       -- Viscosit
                                                            y out

// Call seqeunce handler for motor speed line 2
      CALL  "SeqHandler"                                    FC1                 -- Sequence
                                                             Handler
       Seq:="Motor_SequenceDB_seqB".Seq                     P#DB5.DBX0.0        -- Sequence
                                                            data
// Her mappes output til motor/ventil handlerens program output


// Her mappes output til motor/ventil handlerens program output


//Reset second pulse
      SET
      R     M    110.0
```

Appendix B – Placement of the mud sampling system



Appendix C – Layout of the mud sampling system

Designed in cooperation with National Oilwell Varco Inc.