NTNU – Trondheim
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Fault Tolerant Control for automated Managed Pressure Drilling

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Master of Science in Engineering Cybernetics (2)
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PROJECT DESCRIPTION SHEET

Name of the candidate: Jarle Eilerås

Thesis title (Norwegian):

Thesis title (English): Fault tolerant control in automated managed pressure drilling

Background

As production on the Norwegian shelf enters tail production, drilling wells with vanishing pressure windows becomes more attractive. This motivates use of automatic control systems for controlling downhole pressure using Managed Pressure Drilling (MPD) techniques. At the same time, in drilling the consequences of faults can be substantial (in terms of cost, human lives and environment), such that increased automation should not lead to increased risk of adverse incidents. Introducing Fault Tolerant Control (FTC) is a step in this direction.

The candidate should explore the possibilities of using FTC in a MPD pressure loop, where choke, back-pressure pump and (possibly) main pump are controlled. Procedures described in the book "Diagnosis and Fault-Tolerant Control" by Blanke et al. should be a starting point.

Work description

1. Give a brief overview of drilling automation; challenges, potential and MPD technology.
2. Give a brief overview over FTC (and possibly fault detection).
3. List and classify and faults that can occur in the automated MPD solution.
4. Suggest control structures that are tolerant for some of the faults.
5. Implement and illustrate in simulations.
6. If time permits: Discuss implementation, and develop schemes for fault detection.
7. Discuss and evaluate the solution.

Start date: 9 January, 2012 **Due date:** xx June, 2012

Supervisor: Lars Imsland
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Trondheim, __13.01.2012__________

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Fault tolerant control for automated managed pressure drilling

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Department of engineering cybernetics— NTNU 2012

Abstract

I de siste årene kostnaden for rigg utleie blitt svært høy. For å redusere totalkostnaden har det vært nødvendig å øke kostnadseffektiviteten ved boring.

En måte å forbedre resultatet er å redusere ikkeproduktivtid, i forhold til feil og utstyr svikt som kan oppstå under boring. I tillegg starter mange av oljefeltene i Nordsjøen haleproduksjon der trykketvinduet er smalt, noe som betyr at trykkbalansert- eller underbalansertboring må brukes.

Denne oppgaven kombinerer feiltolerantkontroll og trykkbalansertboring for å se på mulingheten til å fortsette boringen ved feil i systemet. Det feiltolerante styresystemet er basert på modell matching.

Simulering er gjort med regulerings ventil blokkert i lukket stilling slik at mottrykkespumpen brukes til å kontrollere bunn trykket i brønnen. Simuleringen er gjort med MATLAB. Simuleringen er gjort for å se om det er mulig å bruke mottrykk pumpen hvis regulerings ventilen er sperret, slik at boringen kan fortsette svikt i regulerings ventilen, noe som normalt ville resultere stopp av boringen. En enkel hydraulisk modell er brukt i simuleringen. Aktuator dynamikk er ikke implementert i modellen.

Resultatet er positivt, mottrykks pumpen kan brukes til å kontrollere bunntryppet i brønnen nåe en benytter trykkbalansertboring. Resultatene viste at ved overgangen mellom normal drift og system med feil ga initialiserings problem som fører til uønskede sprang.

Sammendrag

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Contents

List of Figures

List of Tables

Nomenclature

BHP	Bottom hole pressure
BOP	Blow out preventer
CBHP	Constant bottom hole pressure
DGD	Dual gradient drilling
DP	Dynamical positioning
ECD	Equivalent circulation density
FTC	Fault tolerant control
I/O	Input output
IADC	International association for drilling contractors
LQC	Linear quadratic control
MPC	Model predictive control
MPD	Managed pressure drilling
NMPC	Nonlinear model predictive control
NPT	Non productive time
PID	Proportional integral derivative
PMC	Pressurized mud cap
PMS	Position mooring system
PWD	Pressure wile drilling
RCD	Rotary control device
ROP	Rate of penetration
UBD	Under balanced drilling
UPS	Uninterrupted power supply

Chapter 1

Introduction

Managed pressure drilling has in short time become state of the art way of drilling for petroleum. This because of improved safety by reduced risk for dangerous failures. This makes it possible to drill wells which otherwise would have very high risk for failure. Even with reduced risk there is still room for improvement. If failure of equipment occur, fault tolerant control (FTC) can be used such that drilling still can be done without stop in drilling thus reduce nonproductive time (NPT) which is very costly.

Therefore a fail tolerant control system for managed pressure drilling is presented in this thesis.

This chapter presents reasons for introducing fault tolerant control to managed pressure drilling, then presents the layout of this thesis.

1.1 Previous research

There is not done much research which combines fault tolerant control and managed pressure drilling. Roar Nybœhas written a doctoral thesis which addresses fault detection in drilling[21]. There have been done much research on automated managed pressure drilling in the last years some of the most important papers are done by John-Morten Godhavn, Control requirement for high-end automatic MPD operations[14] , Drilling seeking automatic control solutions[9] and Control requirements for automatic managed pressure drilling system [15]. Other important papers are Simplified hydraulic model for intelligent estimation of down hole pressure for a MPD control system [6] by Glenn-Ole Kaasa et al, Adaptive estimation of down hole pressure for managed pressure drilling operations [29] by Œyvind Nistad Stamnes, Managed pressure drilling: A multi-level control approach [28] Œyvind Breyhotz et al, Evaluating control designs for co-ordinating pump rates and choke valve during managed pressure drilling operations [27] Œyvind Breyhotz et al.

In fault tolerant control there is few papers available one Jin Jiang and Xiang Yu have written Fault-tolerant control system: A comparative study between active and passive approaches [19]. Blanke et al. has written a book about fault tolerant control [11] which describes the essentials for FTC.

The previous work has not combined fault tolerant control system and MPD and therefore it is of interest that some research is done to see if FTC for MPD can be used to reduce NPT.

1.2 Background

Drilling for oil has been done for over a century. During this time there have been steady improvements of efficiency reducing time and risk necessary for developing a oil well. Today there is a high focus on automation of drilling. The oil industry has been very conservative regarding new technology as failures are costly because of the expenses from NPT.

The production of petroleum in the northern sea will in short time enter into tail production on many of the discovered fields, thus fields with small pressure window becomes more attractive. Small pressure window makes it difficult or impossible to drill conventional as the margin between pore pressure and fracture pressure becomes very small. To handle this situation automatic control of bottom hole pressure can be achieved with manages pressure drilling MPD techniques.

A fault tolerant system for automatic control system is wanted to reduce NPT. Therefore it's a necessary goal that implementation of automation increase regularity of it should be applicable for use in a real system. Figure 1.1 shows some of the most important reasons for NPT.

There is written some papers on the problems that is behind non productive time.

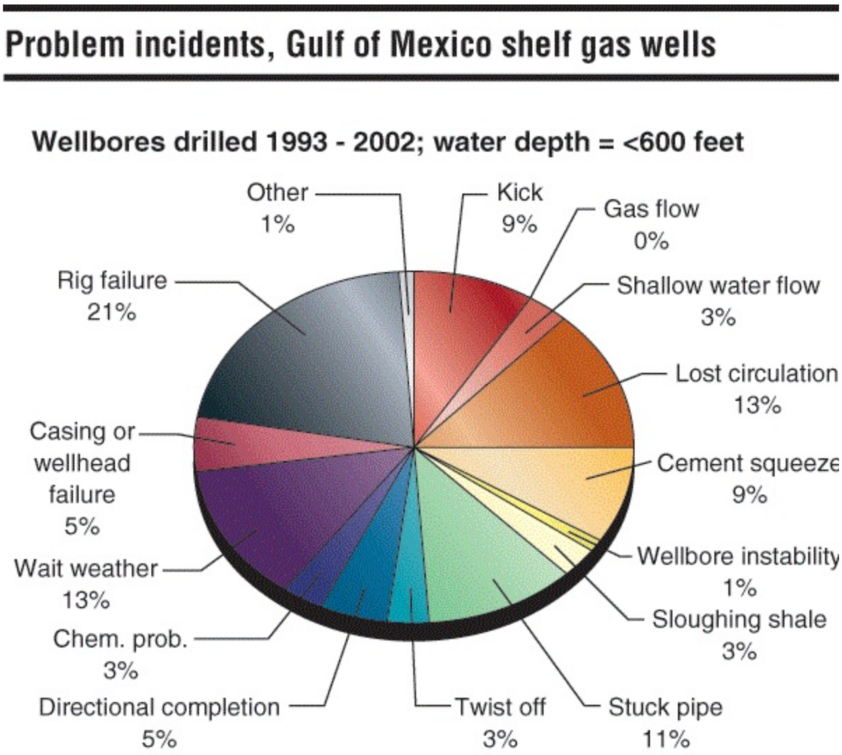

Figure 1.1: Diagram showing reasons for nonproductive time(NPT) in Gulf of Mexico.[1]

1.3 Contribution to science

The essentials for FTC and fault detection are presented. A brief introduction to the systems necessary for conventional drilling is used to give a base for presenting some of the most common faults that which could occur.

The thesis will look into how different faults in a managed pressure drilling system could be managed such that drilling with a faulty system can resume while the fault is fixed. To do this a brief overview of the most common faults and classification is done.

The thesis goes in depth on choke failure and pressure sensor failure and applies FTC and simulated. A model matching approach is used, where analytical redundancy instead of physical redundancy is used. The goal is to used FTC such that back pressure pump can be used alone to manage pressure if the choke valve fails.

1.4 Report structure

Chapter 2 is a presentation of FTC techniques and fault detection. The chapter starts with basics about FTC like faults and system structure and architecture. Then a formalization of the control problem, model matching, control re-configuration and at last some basics on consistency based diagnosis and diagnosis structures.

Then chapter 3 presents MPD. The chapter starts with presenting the different systems which are required for conventional drilling. Then MPD variations are presented. A brief description of under balance drilling (UBD) is presented to state the difference between MPD and UBD. Then at last some of the fault which can occur during drilling is presented.

Chapter 4 presents a hydraulic model for FTC which has used for developing a FTC system for MPD. A nominal model for normal operation is first presented then the faults presented in chapter 3 is classified. Then at last a FTC system is presented where model matching is used.

In chapter 5 results from simulation are presented.

Discussion of faults and results is done is chapter 6.

At last in chapter 7 a conclusion for this thesis is presented together with a suggestion for further work.

Chapter 2

Fault-tolerant control

Modern drilling has huge interests in reduced NPT as the cost for rig rental and exploration cost have increased dramatic the last years. Thus, fault-tolerant control (FTC) may be a way to reduce NPT. This chapter presents some basic about FTC and diagnosis.

The theory in this chapter is based on Diagnosis and fault-tolerant control by Mogens Blanke at al. [11]. The book generalize the regular control problem and introduces faults in the system. It presents methods for diagnosis and recovery by utilizing analytical redundancy instead of physical redundancy.

The chapter starts with presenting main concepts in FTC before some more formal definition of what a fault is and how fault can be classified and system structures and architecture used in FTC systems.

Then the control problem is formalized and presented with control structures, model matching and control re-configuration and transient handling. The at last some basics on fault detection and diagnosis. Here consistency based diagnosis is presented together with and diagnosis structures for distributed and remote systems

2.1 Basics

A fault is something that changes the behavior of a system such that the system does no longer satisfy its purpose.

In complex systems different subsystems interact with each other in a fashion where a single fault in an one system changes all the other systems performance.

Therefore, control equipment should be chosen such that the system is fault tolerant. The intention is that even when there is a fault in a system the system can maintain its original objective, even if there may be a short time with degenerated performance. Thus the control system has to adapt to the possible faults that can occur in the system.

Fault tolerant control handles the interaction between system and controller. An additional layer is introduced into the control algorithm that determines; what is the most appropriate control configuration for a set of faults.

Fault diagnosis is an algorithm that identifies faults with a specific method. While controller redesign uses fault knowledge to determine what is appropriate control values for the system.

Fault tolerance can be very complicated to implement and it is usually only done for safety-critical equipment. There have to be some sort of measurement signal that the diagnosis algorithm can use to determine if there is a fault in the system. The most important measurement signals are done with more than one instrument to secure physical redundancy.

Redundancy can be achieved in other ways like using analytical redundancy where a mathematical model performs the two steps of fault-tolerant control. The use of analytical redundancy is cheaper than using physical redundancy.

In general there are two steps for making a system fault tolerant.

1. **Fault diagnosis**
2. **Controller redesign**

These steps are carried out in a supervision layer that determines algorithms and parameters of the controller.

2.1.1 System structures and architecture

Fault tolerant control uses two layer architecture, a executive layer and a supervision later. The executive layer contains the control loop (controller and plant), while the supervision later contains the diagnosis and control re-configuration blocks.

Figure 2.1 shows the architecture of a fault tolerant control system. The figure shows a regular feedback structure consisting of a controller and a plant at an execution level. On a supervision level there is a controller re-designing block and a diagnosis block, where the diagnosis block interpret the plant condition and to diagnose its condition and feeds this into the controller re-design block, which decide which controller to use based on the diagnosis that is appropriate to influence the plant.

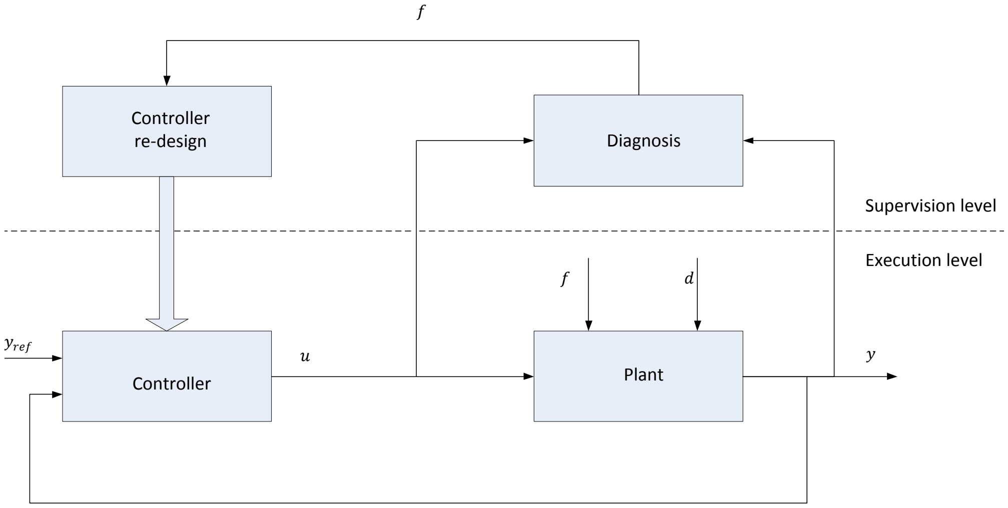

Figure 2.1: General architecture to diagnosis, supervise and control plant with fault tolerant control.[11]

The diagnosis uses the input u and output y and test this with a model of the plant. The diagnosis block then outputs a classification of the system which decides if there is a distinct fault in the system.

The re-design block uses the classification f from the diagnosis block to determine the appropriate adjustment of the controller.

In a faultless case the system controller adjust for disturbances d in the system, and no action is necessary for the supervision level as the diagnosis block recognize the system as faultless.

When a fault f occurs the diagnosis block identifies the fault and the controller reconfiguration changes the controller accordingly.

Since faults disturbances and model uncertainties sometimes can be indistinguishable the fault f is not always distinguishable such that only an fault estimate $\hat{f}$ of the fault of a set $\mathcal{F}$ of candidates is available.

There are other methods for FTC where other structures are used.

- Robust control, is also known as passive fault tolerance. It has the limitation that a controller with fixed parameters handles all faults and will perform suboptimal for most faults if it can handle them.
- Adaptive control is also known as active fault tolerance. It has the limitation that it is only efficient for linear plants where the parameters are slowly varying.

The difference with FTC is that parameters and model behavior can be very different from the nominal plant and nominal controller.

At component level a single fault on a component propagates through the overall system. A simple fault in a component can initiate the safety system in some instance. The fault propagation can be stopped by making the component fault tolerant. Propagation of fault usually takes some time before it propagates thus there is some time for the controller to adjust for the behavior.

2.1.2 Faults

A fault is a deviation from the systems nominal parameter or structure. In these cases the system-controller interaction would change and thus some changes have to be done to take the system back to normal performance, as the original input/output (I/O) changed when there is a fault in the system. Faults can be recognized by a systems behavior. If you know how a system normally responds and then the system has a completely different response you start investigate if there is something wrong. To formalize this:

Suppose a plant $f(x, u, f)$ and a fault tolerant controller $f(y)$ such that

$$\begin{aligned} y &= f(x, u, f) \\ u &= f(y) \end{aligned} \tag{2.1}$$

where f is the fault in the system. The input is denoted u, the plant state is denoted x, and the measured outputs is y. Defines the set $\mathcal{F}$ for which all faults where the system function is retained. The faultless case is denoted f_0 and $f_0 \in \mathcal{F}$. The input u and the output y represents a space $\mathcal{U} \times \mathcal{Y}$ which represents the possible combinations of I/O signals. The behaviour $\mathcal{B}$ is a subset $\mathcal{B} \subset \mathcal{U} \times \mathcal{Y}$ where $\mathcal{B}$ is possible I/O for a specific system.

Given a I/O pair $A(u, y)$ and $C(u_C, y_C)$ where C is not consistent with the system A thus gives $u \to y \neq y_C$

For example, given the system

$$y(t) = k_s u(t) \tag{2.2}$$

where k_s is a constant. The set of all I/O pairs is

$$\mathcal{B} = (u, y) : k_s u \tag{2.3}$$

which can be represented as a straight line. If the system suddenly does not comply to this behavior of 2.3 and for example output is formed as quadratic signal $k_s u^2$, which is a I/O pair that does not belong to $\mathcal{B}$ then a fault can be found in the system, this because the system does not have consistent behavior known for a fault less system.

When working with dynamic system the whole time sequence for each signal must be considered such that for a discrete-time system

$$\begin{aligned} U &= (u(0), u(1), ..., u(k_h)) \\ Y &= (y(0), y(1), ..., y(k_h)) \end{aligned} \tag{2.4}$$

where k_h is the time horizon. The systems possible I/O pairs also changes such that

$$\begin{aligned}&\mathcal{U} \times \mathcal{Y} = \mathbb{R}^{k_h} \times \mathbb{R}^{k_h}\\&\mathcal{B} \subset \mathbb{R}^{k_h} \times \mathbb{R}^{k_h}\end{aligned} \tag{2.5}$$

were $\mathcal{B}$ represents the faultless plant I/O pair sequences.

Given a system where $A = (U, Y_A) \in \mathcal{B}_0$ represents a faultless system and $B = (U, Y_B) \in \mathcal{B}_f$ is a system with a fault. Then a fault can be isolated if the behavior $\mathcal{B}_f$ does not intersect $\mathcal{B}_0$

The nominal mathematical model represents a constraint for the set $\mathcal{B}_0$ and the I/O pair. For dynamic systems the $\mathcal{B}_0$ is represented with a differential equation for continuous time system or equivalently a difference equation for a discrete time system.

In fault diagnosis the constraints is used to determine which I/O pair is consistent with the nominal signals U and Y for a faultless system $\mathcal{B}_0$. In other word determine which behavior the I/O pair (U,Y) belongs to.

The difference between disturbance and fault

In an analytic model there are two different faults that can occur.

- Additive fault, here there is an additional unknown term in the equation
- Multiplicative fault, here a fault represented as a system parameter is multiplied with either a system state or input.

The nominal plant behavior can be subjected to disturbances and model uncertainties. Model disturbances and uncertainties interact with the system in similar ways as additive and multiplicative faults. Disturbances influence the system in the same manner as an additive fault, while model uncertainties influence the system like a multiplicative fault.

The difference are that faults should be detected if their effect are to be removed, while disturbances and uncertainties have limited effect on the system performance and can be handled appropriate controller design. Faults are changes in the system that requires changes in the controller design.

Fault classification

Given a system consisting of actuators, plant and sensors a fault could happen in any of these parts of the system, and can therefore be described as:

- Actuator faults: The controller may lose degrees of freedom to interact with the plant.
- Plant faults: The systems dynamic properties are changed thus changing the I/O properties.
- Sensor faults: Sensors have errors in the readings which can be huge.

In figure 2.2 the different fault classes are illustrated mathematically. There are methods for detecting and re-configure actuator and sensor faults. From a diagnosis perspective this is not considered more in this thesis but controller re-configuration of these fault are presented later.

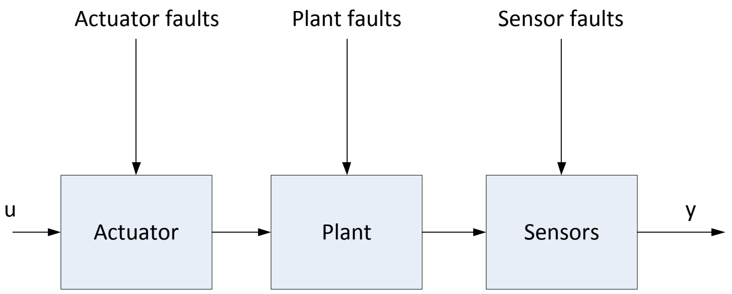

Figure 2.2: Classification of faults.[11]

The difference between fault and failure

If the system cannot accomplish its function there is a failure. The difference is that, for a fault there exist an alternative when using FTC, but a failure implies that the system have to shut down and repaired before it can accomplish the nominal system function.

Faults can cause damage to machinery and environment and risk for humans, therefore different methods for handling these faults is also handled by a separate system for safety.

Safety systems are control equipment that protects the system from permanent damage. Some of the most important definitions regarding requirements for systems subjected to faults are:

- Safety, it is the absence of danger. Safety systems are installed to protect plants from permanent damage and a fail-safe system has the ability to take a system into a safe state if a fault or failure occurs in the system.
- Reliability is the probability that the system accomplish its intended function.
- Availability is the probability that a system can be operated when needed.
- Dependability lumps together the three other properties,

In a fault-tolerant system, a faults does not develop into failures and thus the system remains operative. The system is said to be fail-operational if the system performance remains the same after a fault. If the system have reduced performance after a fault the system is said to be fail-graceful.

Figure 2.3 shows safety related regions that have to be considered when using FTC. The region of required performance is where the system is in normal operation and the controller makes the system states converge to this region regardless of disturbances and uncertainties.

The degraded performance set are faulty systems area of operation. In this region the system can have severely reduced performance.

Unacceptable performance is when the system failures. The system should never reach this region. To avoid the region of unacceptable performance FTC should be used. If the system enters this region the safety system should intervene to hinder failure where the system enter region of danger.

A system should never reach the region of danger. In this region the system may cause damage to environment or people.

Since the FTC system and safety system have different regions this means that a FTC system does not considerate safety but focus on keeping the system up and running with faults.

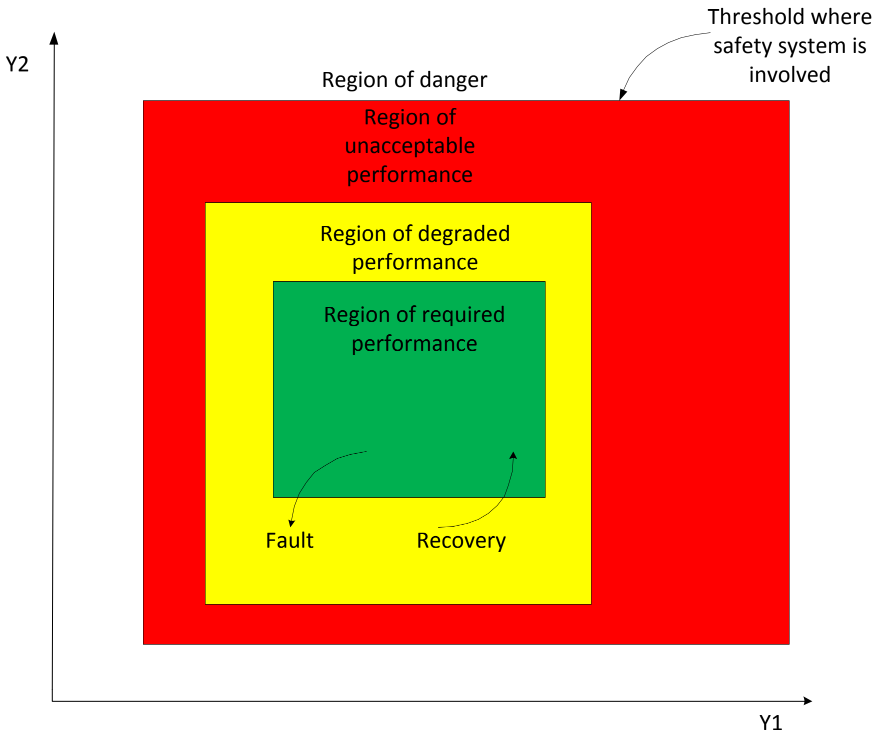

Figure 2.3: Control performance set.[11]

2.2 Control problem

FTC is an expansion of the regular control problem, but there are different methods for solving the extended FTC problem. Two of them are formalized. The formalization can be simplified for special cases which makes it simple to find new control law for some faults.

2.2.1 Problem definition

In standard control problem definition there is a set of objectives constraints and control laws that need to be defined.

Definition 1. *(The control problem)*
Solve the problem $< O, C, U >$

Here O is the objective of the system. The objective can be very specific or more general like giving closed loop stability for the system.

The constraints C is the constraints that the system must satisfy over time. These can be described with algebraic and differential equations when considering continuous systems. The constraints could be equality constraints or inequality constraints or both.

Admissible control laws is defined with the set U, it contains the possible control laws that can satisfy the system objectives. There is usually a mapping from a reference value to a control space.

When faults are introduced to the control problem a very different situation appears, the constraints and admissible set are no longer static. There are two different problem definitions for this set of problem and they have very different approaches for solving it.

Definition 2. ***(Fault accommodation)***
Solve the problem $< O, \hat{C}_f(\hat{\theta}_f), \hat{U}_f >$*, where* $\hat{C}_f(\hat{\theta}_f)$ *is the estimate of the actual constraints provided by diagnosis algorithms.*

Definition 3. ***(Reconfiguration)***
Find a new set of system constraints $\hat{C}_f(\hat{\theta}_f)$ *such that the control problem* $< O, \hat{C}_f(\hat{\theta}_f), \hat{U}_f >$ *have a solution, find and activate this solution.*

A generalization of the FTC is the supervision problem, which arise when accommodation or reconfiguration fails to find a solution. This problem introduces a new variable such that four sets are analyzed. The supervisor problem is a fault tolerant control problem with an additional set for possible control objectives. This implies that the system's objective has to be determined.

In some extreme cases there is no solution for the supervision problem. In this case the system does a controlled failure where the safety system takes the system to a safe state.

2.2.2 Model matching

Assuming the model can be described with the state-space model

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{g}(\mathbf{x}(t), \mathbf{u}(t), f), \quad \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{y}(t) &= \mathbf{h}(\mathbf{x}(t), \mathbf{u}(t), f) \end{aligned} \tag{2.6}$$

the fault tolerant control problem can be defined as

Problem 1. ***(Fault tolerant control problem)***

Given:	*Model (2.6) of the plant* *Nominal controller* $\boldsymbol{k}$ *Control specifications.* *Fault* f
Find:	*Control configuration and new control law* $\boldsymbol{k}_f$

In this problem definition a nominal controller $\mathbf{k}$ is known, has the advantage that there exist some stable closed-loop. Therefore there exist some feedback controller $u(t) = -Kx(t)$ which gives the model

$$\begin{aligned} \dot{\mathbf{x}}(t) &= (\mathbf{A} - \mathbf{B}\mathbf{K})\mathbf{x}(t) \\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t) \end{aligned} \tag{2.7}$$

If a fault occurs there is a change in the system such that the system changes to

$$\begin{aligned} \dot{\mathbf{x}}(t) &= (\mathbf{A}_f - \mathbf{B}_f\mathbf{K}_f)\mathbf{x}(t) \\ \mathbf{y}(t) &= \mathbf{C}_f\mathbf{x}(t) \end{aligned} \tag{2.8}$$

And from this the relation

$$\mathbf{A} - \mathbf{B}\mathbf{K} = \mathbf{A}_f - \mathbf{B}_f\mathbf{K}_f \tag{2.9}$$

For this the relation (2.9) is only true if the image of $\mathbf{B}$ and $\mathbf{B}_f$ is similar. In this case the controller $\mathbf{K}_f$ is chosen to minimize the norm

$$||\mathbf{A} - \mathbf{B}\mathbf{K} - (\mathbf{A}_f - \mathbf{B}_f\mathbf{K}_f)|| \tag{2.10}$$

One solution for 2.10 uses the pseudo inverse, thus giving it the name pseudo-inverse method. To ensure the stability for the faulty plant an extension of this solution has to be done if there is not a separate test for the faulty situations.

For actuator faults or sensor faults there exist special cases for determine the controller gain, which simplifies the problem.

Figure 2.6 shows the schematic similarity between a nominal plant and a faulty plant when using model matching. As can be seen the controller is designed such that the control loops are equal.

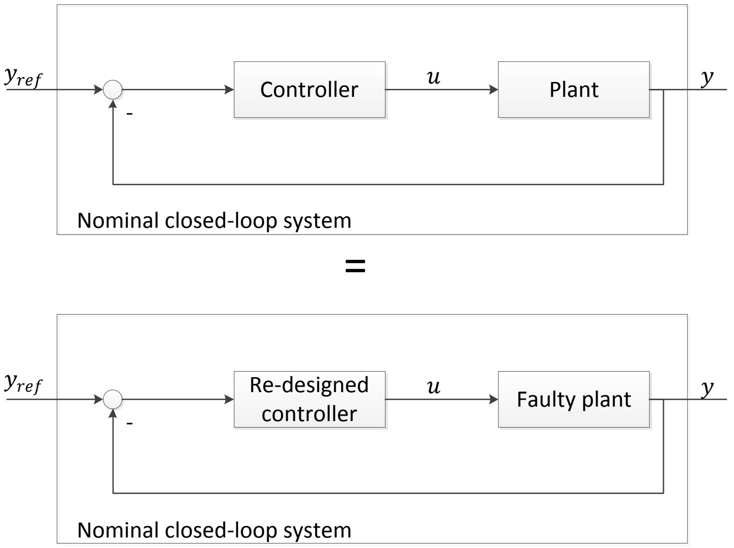

Figure 2.4: Idea of model-matching approach to control reconfiguration.[11]

Model matching for sensor faults

If a sensor fails an element in the C matrix vanish and set the corresponding output y to zero and changes y such that$\mathbf{C} \to \mathbf{C}_f$ where one row is zero.

For this problem there exists a simplified solution of equation (2.9) where

$$\mathbf{K}\mathbf{C} \quad = \quad \mathbf{K}_f\mathbf{C}_f \tag{2.11}$$

which only is satisfied if there exist a kernel matrix of the failure matrix

$$kernel(\mathbf{C}_f) \subseteq kernel(\mathbf{C}) \tag{2.12}$$

or

$$rank\mathbf{C}_f \quad = \quad rank \begin{pmatrix} \mathbf{C} \\ \mathbf{C}_f \end{pmatrix} \tag{2.13}$$

From this a lemma can be derived.

Lemma 1. *In case of sensor failures, exact model matching can be reached if the relation (2.13) holds. The the controller*

$$\boldsymbol{u}(t) = -\boldsymbol{K}\boldsymbol{P}\boldsymbol{y}(t) \tag{2.14}$$

solves the reconfiguration problem where

$$\boldsymbol{P} = \boldsymbol{C}\boldsymbol{C}_f^{+} = \boldsymbol{C}\boldsymbol{C}_f^{\prime}(\boldsymbol{C}_f\boldsymbol{C}_f^{\prime})^{-1} \tag{2.15}$$

satisfies the relation

$$\boldsymbol{C} = \boldsymbol{P}\boldsymbol{C}_f \tag{2.16}$$

This produces a reconfigured controller $\mathbf{K}_f = \mathbf{K}\mathbf{P}$ were the faulty system and the faultless system have exactly similar closed loop properties.

Model matching for actuator faults

For actuator fault there exists a simplification of the pseudo-inverse method. Here the relation (2.10) is simplified to

$$\mathbf{BK} = \mathbf{B}_f\mathbf{K}_f \tag{2.17}$$

and a solution only exist if the image of $\mathbf{B}$ and $\mathbf{B}_f$ have the relation

$$Im(\mathbf{B}) \supseteq Im(\mathbf{B}_f) \tag{2.18}$$

or equivalently that

$$rank(\mathbf{B}_f) = rank(\mathbf{BB}_f) \tag{2.19}$$

From this a lemma can be stated.

Lemma 2. *In the case of actuator failures, exact model matching can be reached if equation 2.19 holds. Then the reconfigured controller is given by*

$$\boldsymbol{u}(t) = \boldsymbol{NKy}(t) \tag{2.20}$$

where

$$\boldsymbol{N} = \boldsymbol{B}_f^{+}\boldsymbol{B} = (\boldsymbol{B}_f^{'}\boldsymbol{B})^{-1}\boldsymbol{B}_f^{'}\boldsymbol{B} \tag{2.21}$$

is a matrix satisfying the relation

$$\boldsymbol{B}_f\boldsymbol{N} = \boldsymbol{B} \tag{2.22}$$

In a similar way as with the sensor failure the new controller $\mathbf{K}_f = \mathbf{NK}$ gives closed loop stability where the faulty system and the nominal system have exactly the same properties.

Control reconfiguration using virtual actuators and/or virtual sensors

An alternative to the model matching approach is the use of virtual actuators and virtual sensors.

Here reconfiguration is done by using a reconfiguration block that utilizes an observer scheme which reproduce lost measurement $y(t)$ or actuator values $u(t)$. The reconfigure goal is divided into a strong goal and a weak goal. Where the strong goal is

$$\mathbf{y}_f(t) = \mathbf{y}(t) \tag{2.23}$$

holds for any disturbance $\mathbf{d}(t)$, $\mathbf{y}_{ref}(t)$ and $\mathbf{x}_0$.

The weak goal is defined as

$$\mathbf{y}_f(t) \rightarrow \mathbf{y}(t) \quad \text{for} \quad t \rightarrow \infty \tag{2.24}$$

This method is not used in this thesis but it is an important alternative to the model matching method, which is important in FTC.

Figure 2.5 shows how control reconfiguration uses a nominal controller and a reconfiguration block.

2.2.3 Controller redesign

Controller redesign aims to satisfy the requirements on the closed-loop system despite the system fault. From a behavioral point of view the set $\mathcal{B}_{spec}$ indicates the wanted specification for the controller that makes the system behave sufficiently. The controllers behavior is defined as $\mathcal{B}_C$ and the relation to $\mathcal{B}_0$ and $\mathcal{B}_{spec}$ is:

$$\mathcal{B}_0 \cap \mathcal{B}_C \subset \mathcal{B}_{spec} \tag{2.25}$$

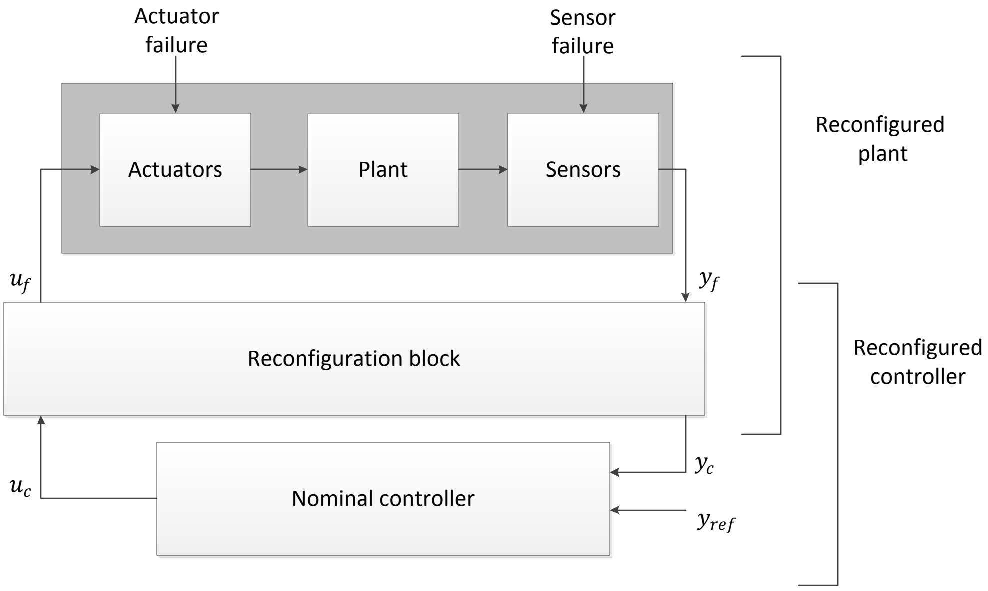

Figure 2.5: Principal of control reconfiguration for actuator of sensor faults.[11]

Thus the systems closed loop performance satisfies the specifications for system performance.

If there is a fault in the system then $\mathcal{B}_f$ describes the faulty behavior which gives

$$\mathcal{B}_f \cap \mathcal{B}_C \subset \mathcal{B}_{spec} \tag{2.26}$$

If the set $\mathcal{B}_f$ is not confined inside the set $\mathcal{B}_{spec}$ the controller behavior have to be changed thus a controller reconfiguration is necessary for the system to have a behavior $\mathcal{B}_f$ which is inside if $\mathcal{B}_{spec}$. If the controller is changed changing the input to the plant the plant behavior itself is changed. Not all faults can be accommodated inside the set $\mathcal{B}_{spec}$. One example is plants with unstable modes that become uncontrollable or unobservable due to faults in the system.

Figure 2.6 shows the duals $\mathcal{B}_0$ and $\mathcal{B}_{c1}$ always are inside the specification $\mathcal{B}_{spec}$ when the system is faultless, but if there is a fault the plant changes from $\mathcal{B}_0$ to $\mathcal{B}_f$ such that the controller behavior $\mathcal{B}_{c1}$ cannot guarantee operation inside the specification $\mathcal{B}_{spec}$. Therefore the system must change to controller $\mathcal{B}_{c2}$ such that the system still remains inside the specification $\mathcal{B}_{spec}$.

There is two principal ways for to change the control space. They are distinguished by:

- Fault accommodation, here the controller parameters are adapted to the dynamical properties of the faulty plant. This is usually done by designing an off-line controller for the specific fault situation
- Control reconfiguration: The complete control loop is reconfigured. Here alternative I/O pairs are used for the purpose to stabilize the plant depending on the fault in the system.

Usually in a system, failure of actuators leads to uncontrollable states and sensor failures leads to unobservable states. Thus re-design is indeed obvious for the system to remain controllable and observable.

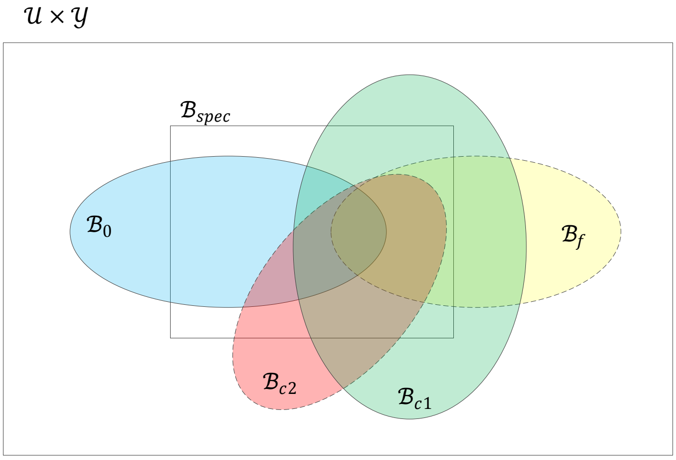

Figure 2.6: Behaviour set relation.[11]

From a real-time point of view the FTC poses new problems beyond the control design.

- The design process has to be completely automatic.
- There have to be a guaranteed solution for the design problem even without optimal performance
- Fault accommodation and controller redesign have to be done under real time constraints.

The real time constraints which are of interest when using fault tolerant control is:

1. Before fault occur the nominal plant is controlled by the nominal controller and the.
2. During occurrence of fault and redesign the nominal control law is controlling the faulty plant and thus the control objective is normally not satisfied.
3. After the fault recovery time the faulty system is controlled using the accommodated or reconfigured control which satisfies the control objectives.

The time window in point two above happens for three reasons and should be made as short as possible.

- Detection time: The time before a fault is detected.
- Fault estimation delay
- Recovery time: The time it takes to recover and redesign the system and bring it back to wanted performance.

For active FTC the isolation delay is unavoidable, this since the system fault have to be identified before an action regarding accommodation can be done. When using reconfiguration the delay can be avoided since it is sufficient to know which component that is faulty and switch it off. When switching controller after recovery time is important that the redesign is bump-less.

Sometimes the system can have degraded performance during a fault in comparison to a faultless system.

2.2.4 Transient handling

Anti wind-up tactics are important when using fault tolerant control. In regular feedback control systems where static laws are used changes between the controllers with equal reference input can be done without taking precaution.

When FTC is used the controller is dynamic, therefore the controllers which is not in the loop have to be initialized correctly when introduced to the loop in order to be bump-less.

One way to achieve this is to feedback the manipulated variable y to each controller regardless if it's the active in the loop or not. The switching between controllers can be done smooth by using a observer-based anti-windup mechanism. The strategy is to feed back the difference $u(t) - u_i(t)$ where i is the i-th. controller.

Figure 2.7 shows a simple scheme for anti-windup.

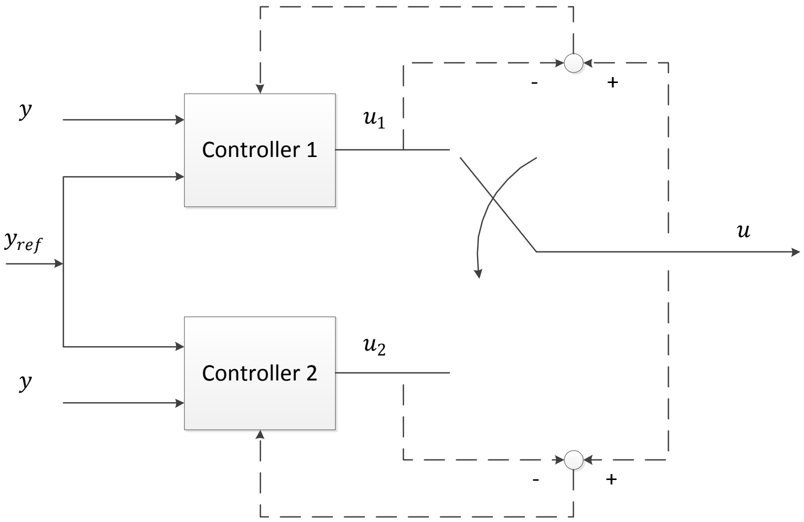

Figure 2.7: A general control scheme for anti-windup mechanism. [11](Insert reference here fig 7.25)

2.3 Fault diagnosis

Detection and identification is one of the important tasks that have to be done before a controller reconfiguration can be done. Thus diagnostic problem considers finding the fault f from the I/O pair (U, Y). The term process diagnostic is used since the diagnostic problem has to be solved in real-time by using the information in a dynamic model.

Diagnosis is done in steps.

- Fault detection: First, a decision, have a fault occurred or is it just a disturbance. Thus deciding when a fault have occurred.
- Fault isolation: Step two, finding the component where the fault has occurred and determine the fault's location.
- Fault identification and fault estimation: Identify fault and estimate of magnitude.

2.3.1 Fault detection

Fault detection is done by using a reference model that predicts the nominal plants behavior is used to compare the I/O pair (U,Y), information given by the plant and plant model. If the model and plant does not consist there is most likely a fault in the system. This is the basis of consistency-based diagnosis.

If the model represents the nominal plant behavior $\mathcal{B}$, a fault is detected if the I/O pair $(U, Y) \notin \mathcal{B}$, which will result in a fault that is not in the set $\mathcal{B}$ and thus is not fault tolerant. If (U, Y) consists with $\mathcal{B}_f$ then there exist some fault candidate f that can be detected from the behavior $\mathcal{B}_f$.

Not all fault are distinguishable given a I/O set (U, Y). In many cases

$$(U, Y) \Rightarrow \{f_0, f_1\} \tag{2.27}$$

and where the fault f_0 is not diagnosable with the given set of I/O.

Consistency based diagnosis is a generalized idea and have several implications.

- Detection can be done with information on the nominal plant alone, no information is necessary about the fault. The idea is to be able to identify deviations from nominal system behavior.
- Information about the fault is necessary to identify the fault. Modeling of the fault response is necessary for faults to be identified.
- By isolating faults the diagnosis excludes fault $f \in \mathcal{F}$. The diagnosis has no way to prove that a fault is present in the system
- Not all faults are distinguishable with a given configuration. Only faults that can be separately identified can be diagnosed.

For continuous system thee is a special cased where the difference between y and an estimate $\hat{y}$ is evaluates such that a residue is present if there is a fault. The residue can be calculated as

$$r(t) = y(t) - \hat{y}(t) \tag{2.28}$$

In a faultless system the residual converges to zero, while a faulty system has a residual that does not converge to zero or diverge to infinity.

Diagnosis for continuous system can be done in two steps.

1. Residual generation: Model and I/O pair determines the residuals and generate the consistency between the plant and the model.
2. Residual evaluation: The residual is evaluated for detect, isolate and identify the fault.

Figure 2.8 shows how the model generates the estimate output $\hat{y}$. Here the estimate $\hat{y}$ can be used for analytical redundancy by comparing it with the real measured output y.

In fault tolerant control the information from system diagnosis should be used for controller redesign. For active fault tolerant control isolation and identification is important, while in safety systems the knowledge about a fault is sufficient. This indicates an important difference between safety systems and fault tolerant systems.

2.3.2 Distributed diagnosis structures

In most literature the embedded system approach is considered. Here all information on the system is available on a single computer board which controls the system directly. In many situations this cannot be done because not all information on the system is available. This is the situation in distributed systems of remote systems.

Distributed diagnosis is necessary when information of the system is distributed between several components that ensures fault tolerance. There are three different situations where distributed diagnosis is concerned.

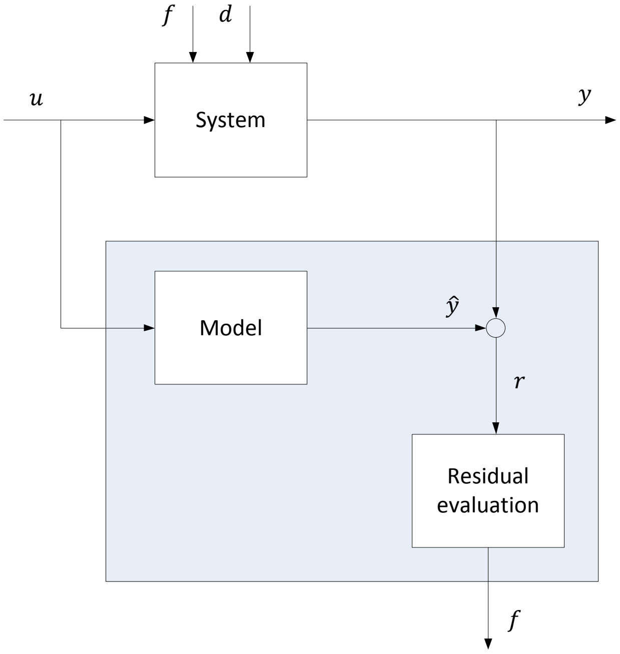

Figure 2.8: Continuous system diagnosis.[11]

- Distributed diagnosis: In a diagnosis system which is distributed the computation efforts is distributed among several components. If the network traffic between the components does not influence the performance a distributed system have the same results as the embedded system approach.
- Decentralized diagnosis: Diagnosis is distributed into sub-problems referring to a corresponding sub-system, where sub-problems are handled independent from each other.
- Coordinated diagnosis: This is like decentralized diagnosis except here a coordination of the sub-problems is done to ensure consistency.

Weakly coupled systems may have advantages when using decentralized and coordinated diagnosis. Such systems usually have subsystems with little interaction between each other.

The problem for decentralized systems are that the no information is shared between the diagnostics systems such that only some faults can be detected in a given subsystem while there are several more faults that can occur in other subsystems that influence the system.

By using a coordinated diagnosis, diagnosis can be done by combining different faults detected in different sub systems thus there is the possibility for accommodating or reconfigure for more faults in the system. The goal is for the coordinate diagnosis to identify all the faults on a global scale. Global detection is the advantage coordination has over decentralized diagnostic.

Remote diagnosis

Modern automation systems may use remote components. These have several more problems which have effect on the diagnosis. This because here on-board and off board components is used. These components are described as under:

- On-board components have limited computing power and memory, limiting its performance.

- Off-board components have almost unlimited computer power, but have to use biased measurements data.
- Data link can cause loss of data and time delay because of limited bandwidth, such that a limited amount of data is transmitted.

The on-board components task is to identify if there is a fault and therefore only need a model of the faultless system running. The off-board component identifies the fault. An important issue of remote diagnosis is the asynchronous operation of the on-board and off-board components.

Chapter 3

Managed Pressure Drilling

This chapter starts with presenting some basics about conventional drilling before managed pressure drilling (MPD) and under balanced drilling (UBD) is presented, this to establish some basics on drilling and explain the difference between the these techniques which are used when drilling for petroleum.

The rest of the chapter then focuses on MPD and challenges and potential with automation of MPD systems. Then at last some of the major faults which is problematic in drilling operations is presented.

3.1 Conventional drilling

The conventional drilling system can usually be divided into several subsystems. Knowledge about these subsystems are necessary for understanding how some of the fault that can occur during drilling.

This section is mainly based on Hydrocarbon exploration and production [5].

A conventional drilling system consists of the following systems. A more detailed presentation is done i the following sub chapters.

- Rotary system
- Hoisting system
- Circulation system
- Power system
- Well control system
- Well monitoring system

3.1.1 Rotary system

Rock penetration is done by applying torque on a hexagonal pipe called a kelly, which rotates the drill string.

The drill string is a connection of different equipment necessary for efficient drilling. At the top of the drill string there is a swivel, which is where the hoisting system is connected to the drill string. The next section is the kelly and kelly saver sub, the saver sub is used to minimize wearing on treads for more expensive equipment. Below the sub is the drill string which consists of several sections with drill pipes, stabilizers for directional drilling and drill collars; for tensioning and adding weight on the drill bit and avoid bucking of the string. In figure 3.1 a simple drill string is illustrated.

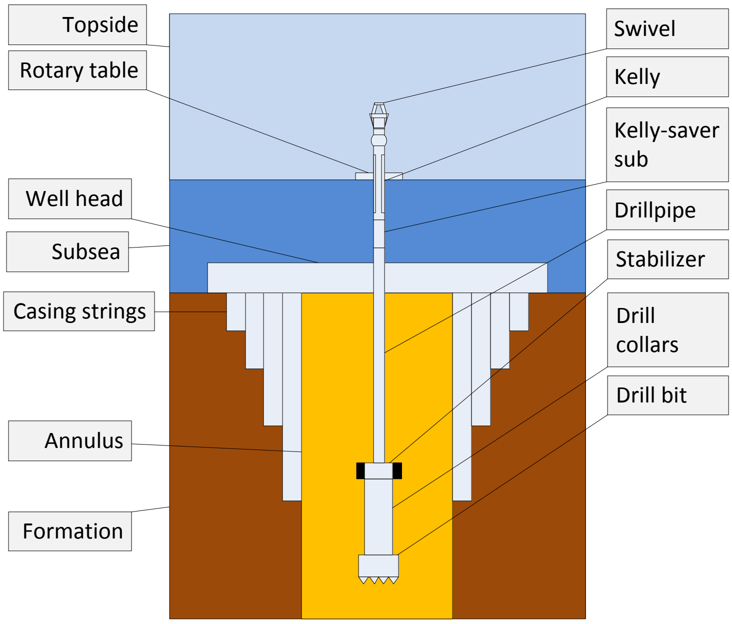

Figure 3.1: Overview of rotary drive system.[5]

3.1.2 Hoisting system

To handle the drill string up and down into the hole and adding pipes to the string a hoisting system is used. The hoisting system is a hook which is attached to the drill string when it is necessary to move shut in drill pipe or making a trip. A shut in is the term for adding a section of drill pipe and a trip is the term for pulling out the whole drill string from the hole.

Figure 3.2 shows a hoisting system.

The hook is connected to a crown block and a draw works by a steel cable.

The hoisting system usually consists of derrick, block and tackle and draw works. It is used to handle drill pipes for new connections and the drill string when making a trip. A trip is when the whole drill string is hoisted out of the well for changing down hole assembly or other tasks that makes it necessary to take the drill string out of the well.

On more modern rigs the hoisting system is automated with robotics that handles drill pipe etc. This is safer since it reduces the necessary manpower on oil deck and dangerous tasks with high risk of injury. This system handles all pipes automatic and pre-assembles pipes increasing the running length for before each connection.

In modern rigs this system is replaced with a top drive, where most handling of drill strings is automated with robots.

3.1.3 Circulation system

A drilling fluid, usually called mud, circulates in the system. The circulation systems task is to cool the drill bit and transport the chippings from the drill bit and up to the surface, to achieve this the mud must have correct viscosity. To hinder influx from the annulus wall the mud also must have correct density.

The circulation system consists of several different components. Mud is stored in mud tanks and is the fluid that circulates in the system. The circulation system is driven by a mud pump. The mud pump can be modeled as an electrical powered hydraulic engine

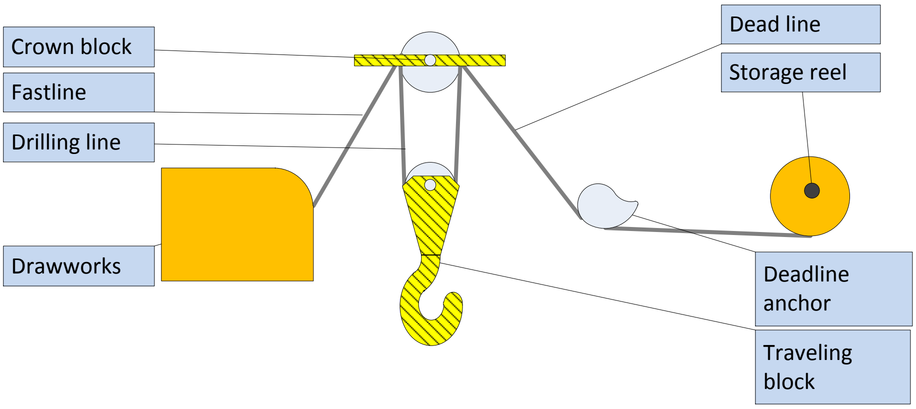

Figure 3.2: Picture of Hoisting system.[13]

[2]. From the mud pump the fluid is pumped through the standpipe and into the drill string out of the drill bit and into the annulus. In the annulus the mud cools the drill bit and transport drill cuttings to the surface to the shale shaker. The shale shaker removes cuttings from the mud. Then the mud is transported into a de-sander and a de-silter which removes finer cuttings. In figure 3.3 the circulation loop is illustrated.

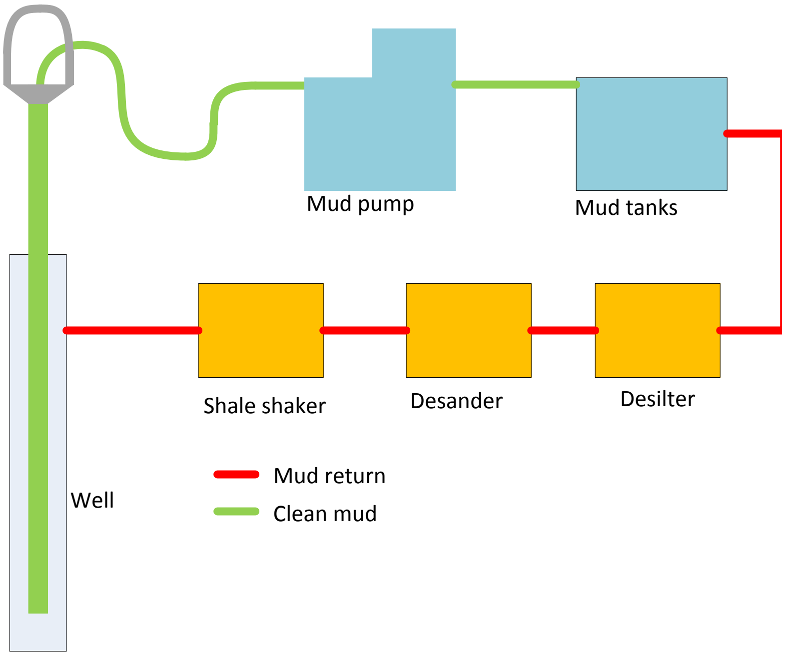

Figure 3.3: Overview of circulation system.[5]

3.1.4 Power system

On an oil rig there is different equipment that applies electric current, but since drilling usually is done where connection to the regular power grid is difficult or uneconomical, the rig is usually powered by diesel engines. These are used to power mud pumps, rotary drive, and hoisting system equipment. For marine rigs it also drives the dynamical positioning system and heave compensation system.

Other power system is the accumulators used for down-hole equipment that monitor the well and transmit measurement to the surface and power logging equipment.

3.1.5 Well control system

Drilling is dangerous work and therefore control over the well has to be achieved at all time. The control system is divided in a safety system which is fail-safe and an ordinary control system for normal operation, which regulates the system.

In conventional drilling mud level is monitored by studying the level of the trip tanks, which are a part of the regular mud thanks, if the measured level deviates from calculated level something is wrong.

Influx into annulus can be extremely dangerous and can lead to what is called a blowout. To handle this blowout preventer (BOP) is installed at the seabed. The BOP seals off annulus and can cut the drill pipe if necessary and then reroute the flow through a choke giving the drill crew time to adjust and rebalance (kill) the well. BOPs are operated by hydraulic accumulators.

Figure 3.4 shows a BOP stack with some of the most common tools on them.

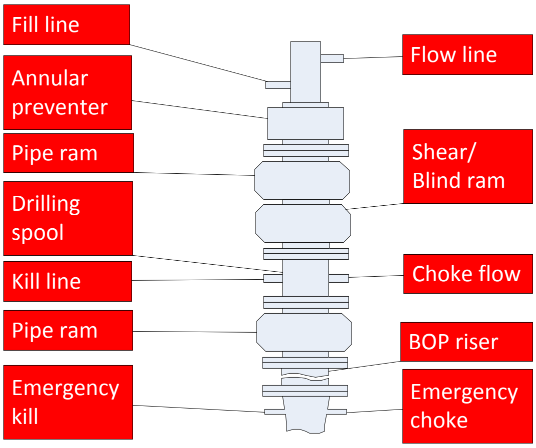

Figure 3.4: Picture of BOP stack.[5]

3.1.6 Well monitoring system

When drilling, there are several parameters that should be monitored simultaneously. If there is a deviation a decision should be done as fast as possible. The driller monitors this in a driller's cabin. Some of the most important to monitor is:

- Depth
- Penetration rate
- Hook load
- Rotary speed
- Rotary torque
- Pump rate

- Pump pressure
- Mud density
- Mud temperature
- Mud salinity
- Gas content of mud
- Gas content of air
- Pit level
- Mud flow rate

3.1.7 Special marine equipment

When drilling for oil, offshore like the northern sea, there are some special equipment that is necessary, this because of the increased complexity that with drilling from a floating vessel, while the blowout preventer is placed on the seabed. The rotary drive and mud pumps is placed on the vessel. To solve this, a marine riser is used that connects the blow out preventer with the vessel. The riser acts as an extension of the annulus.

Waves move the floating vessel in heave direction. Heave movement must be compensated for since the wave motion would otherwise move the drill string up and down increasing and decreasing the pressure on the bore crown, making it impossible to drill.

Heave compensation is used on the vessel and on the derrick floor to minimize heave motion. The heave compensation has a limited working area and therefore drilling cannot be done if the heave motion is to large.

In bad weather the marine riser has to be disconnected from the drilling vessel. The riser has flexible joints to compensate for heave motion and make it possible to disconnect in bad weather.

Floating vessels also have to be positioned correctly. The rig has to be positioned as directly over the bore hole as possible when drilling. This is possible with a position mooring (PM) system or dynamical positioning (DP). In a PM system the vessel is anchored to the seabed. In sea where depth is to large DP systems have to be utilized to hold correct position. Figure 3.5 shows a simple illustration of a PM system.

3.2 MPD drilling

Managed pressure drilling is a standard drilling technique which reduces (NPT) when the wells pressure window is small. In a paper form 2005 Don M. Hannegan[17] write in his conclusion that in the future all wells would have to be drilled under balanced and that MPD is a reasonably step in this direction since more prospects are un-drillable with conventional technology. Most of this section is based on Managed pressure drilling [4].

There are several advantages when using MPD which can reduce cost when developing a well.

- Reduce number of casing points.
- Reduce NPT from stuck pipe.
- Avoiding lost circulation -well kick problem
- Limiting lost circulation

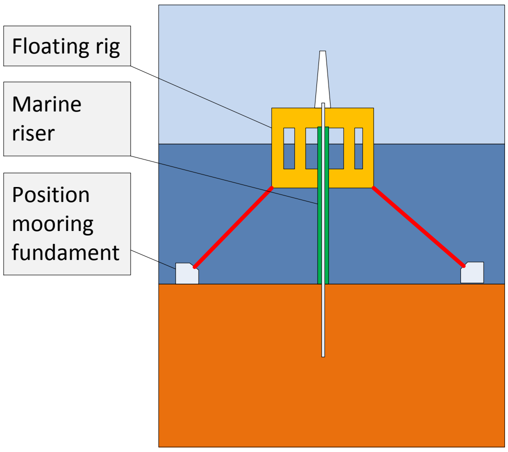

Figure 3.5: Picture of PM system. [5]

- Drilling with total loss.
- Increased rate of penetration
- Deep-water drilling with lost circulation and water flows.

Managed pressure drilling does not invite for influx into the well and therefore is a overbalanced drilling method. MPD uses back-pressure which makes it possible to maintain pressure when circulation is halted.

The increased control over pressure window makes it is possible to drill further before a new casing has to be added when using MPD. Lost circulation can be reduced

MPD have three main variations. a presentation of the key variations is presented.

- Constant bottom hole pressure (CBHP)
- Pressurized mud cap drilling (PMC)
- Dual gradient drilling (DGD)

There exist two different categories of MPD: Proactive and reactive. Reactive MPD closes and pressurize the mud system, but else have a conventional drilling program. While using proactive MPD the whole drilling program is planned to benefit from closed and pressurized mud system. The proactive method gives most rewards offshore since it can reduce risk for nonproductive time.

3.2.1 Pressure window

In conventional drilling and MPD the pressure window is important. The well pressure should not be lower than the pore pressure or higher than the fracture pressure. If this happens there will be an influx of fluid into the well bore or an outflux of mud. In extreme situations influx results in kicks and outflux can damage the formation reducing the possible future production. Figure 3.6 shows how different pressure and depth can vary for some arbitrary well.

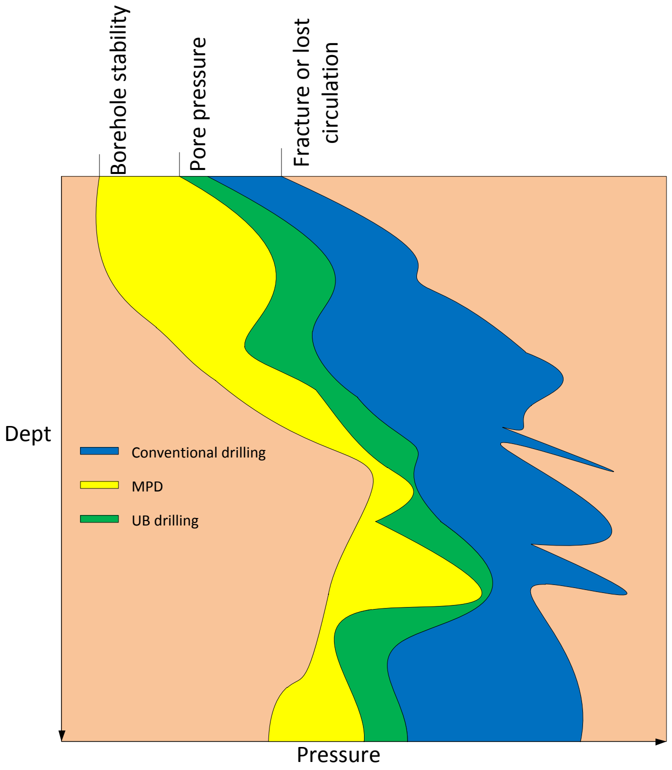

Figure 3.6: Pressure window parameters.[10]

Pore pressure

The pressure in the formation can be calculated from the column of water from the surface. There can be some zones that this gradient doesn't apply because of different geological structures. Log data and seismic data are used to estimate pore pressure and detect zones with different pore pressure. One model which can be used is Eaton's model

$$\text{Pore pressure} = P_{overburden} - (P_{overburden} - P_{Normal})(\frac{\text{Log value}}{\text{Value of normal trend}})^{K} \tag{3.1}$$

Fracture pressure

The overburden pressure and fracture pressure is the highest pressure that safely can be allowed in the well. This pressure differs with regions and formation. The overburden pressure is usually calculated by using rock matrix bulk density since it is not fluid dependent pressure.

$$S = \rho_b \times D \tag{3.2}$$

Where ρ_b is the average formation bulk density, D is the vertical thickness of the overlying sediments.

The average formation bulk density can be expressed as

$$\rho_b = \phi\rho_f + (1-\phi)\rho_m \tag{3.3}$$

where ϕ is the rock porosity;ρ_f is formation fluid density and ρ_m is rock matrix density

The fracture pressure can be described with

$$P_f = (\frac{\upsilon}{1-\upsilon})\sigma + P_P \tag{3.4}$$

where υ is the Poisson's ration, σ is the effective stress on the formation and P_P is the pore pressure.

Calculation of formation pressure can be difficult and therefore some tests are done when deciding the formation pressure. There are two different test which is usually done, formation integrity test and leak-out test.

In the formation integrity test the formation is pressured to a predefined pressure and then hold. This test is usually done in formations where there is knowledge on the formation.

In a leak-out test the pressure is increased until the mud leaks into the formation and the pressure stabilize and decrease after fracture.

3.2.2 Constant bottom hole pressure

In constant bottom hole pressure drilling the main important goal is to hold bottom hole pressure (BHP) within the bounds of pore pressure and fracture pressure.

$$P_{pore} < P_{BHP} < P_{fracture} \tag{3.5}$$

Pore pressure and fracture pressure gives the largest margin, but there exists other pressures that have to be considered which decrease the pressure window. Like well-bore stability P_{wbs}, differential sticking P_{ds} and lost circulation pressure P_{ls}. Thus the window often can be described with:

$$P_{pore} < P_{wbs} < P_{BHP} < P_{ds} < P_{ls} < P_{fracture} \tag{3.6}$$

BHP can be calculated easily with assuming a column of circulating water. Thus the BHP for a pressurized well can be calculated

$$BHP = P_{static} + P_{friction} + P_{pump} \tag{3.7}$$

There exist several different models for calculating the static and frictional pressure.

When using back-pressure control, P_{pump} can be regulated. To seal annulus a rotating control device (RCD) is used.

There are several ways to implement the choke control system.

- Control method
- Integration of choke control and hydraulics model.
- Use of on-line pressure data from the well to update hydraulics model.
- Real-time capacity of hydraulics model.
- Adding back pressure with back-pressure pump

The choke control can be automatic, manual of semi-automatic. Choke design are very robust. This is necessary since the mud have high wear on the choke, because of this chokes are usually physical redundant.

Hydraulic models are usually used in dynamic annular pressure control systems. The hydraulic model estimates the down-hole pressure or uses real-time data from pressure wile drilling (PWD) systems and output a desired choke pressure [6]. Control accuracy is limited by the least accurate term, such that a hydraulic model doesn't have to be very complex before measurement with high uncertainty influence accuracy. In more complex models there are parameters which need measurements along the whole drill string.

From a control systems view there are three factors which motivates for a simple model.

Table 3.1: Parameter legend for hydraulic model [6]

V_d	Volume in drill string
β_d	Bulk modulus in drill string
p_p	Mud pump pressure
q	Flow through bottom hole
q_p	Flow through mud pump
V_a	Volume in annulus
β_a	Bulk modulus in annulus
q_{bpp}	Flow through back-pressure pump
q_c	Flow through choke valve
M	Is the integrated density per cross-section over the flow path
$F(q,\mu)$	Pressure loss because of friction. Dependent of flow and viscosity
$G(\rho)$	Hydrostatic pressure. Dependent on mud density

- Bandwidth of control system
- Robustness of the implemented algorithm
- On-line calibration of the hydraulic model.

The bandwidth is an upper limit for which the control system can compensate for changes. In a MPD system this is limited by measurement sampling interval and actuator dynamic.

Algorithm robustness can be easy to prove for simple algorithms while for more complex models this can be very computational time consuming. Online calibration of complex models usually must be done manually by an expert, while simple models exist for on-line parameter estimation.

Stability analysis can also be very difficult for complex models. Thus stability proof can therefore be difficult.

In the paper Simplified hydraulics model used for intelligent estimation of down hole pressure for MPD control system [6] a simple hydraulic model for automatic MPD is derived which calibrates itself automatically on-line.

$$\begin{aligned} \frac{V_d}{\beta_d}\frac{dp_p}{dt} &= q_p - q \\ \frac{V_a}{\beta_a}\frac{dp_c}{dt} &= -\frac{dV_a}{dt} + q + q_{bpp} - q_c \\ M\frac{dq}{dt} &= \begin{cases} p_p - p_c - F(q,\mu) + G(\rho) & q > 0 \\ max(0, p_p - p_c - F(q,\mu) + G(\rho)) & q = 0 \end{cases} \end{aligned} \tag{3.8}$$

The model parameters is described in table 3.1 .
and down hole pressure can be calculated with

$$p_{dh}(l) = p_c + F(l,q,\mu) - G_a(l,\rho) \tag{3.9}$$

The frictional pressure loss $F(l,q,\mu)$ may have different complexity. One simple model is $F(q) = C_a q^2$, and static pressure $G(\rho) = \rho_a g h$.

One of the advantages when using a hydraulic model is that equivalent circulation density (ECD) is constant during drilling.

Figure 3.7 shows a flow diagram which can be interpreted as the drill string. The mud pump q_p and back pressure pump q_{bpp} adds mass to the system, the choke q_c removes mass from the system, q_b is a one way valve such that mud in the annulus cannot flow into the drill pipe.

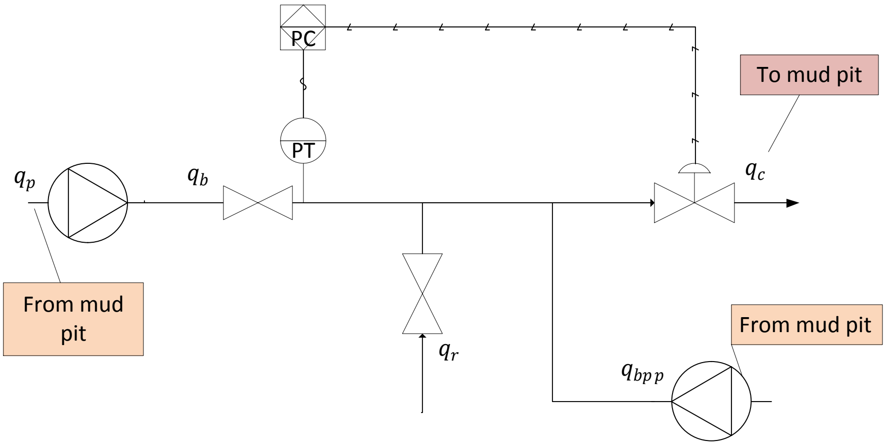

Figure 3.7: Flow schematic for constant bottom hole pressure method.[8]

Figure 3.8 show the pressure gradient for CBHP in compared with conventional pressure gradient. From the figure it can be seen that adding back pressure gives an advantage since the pressure gradient can be changed.

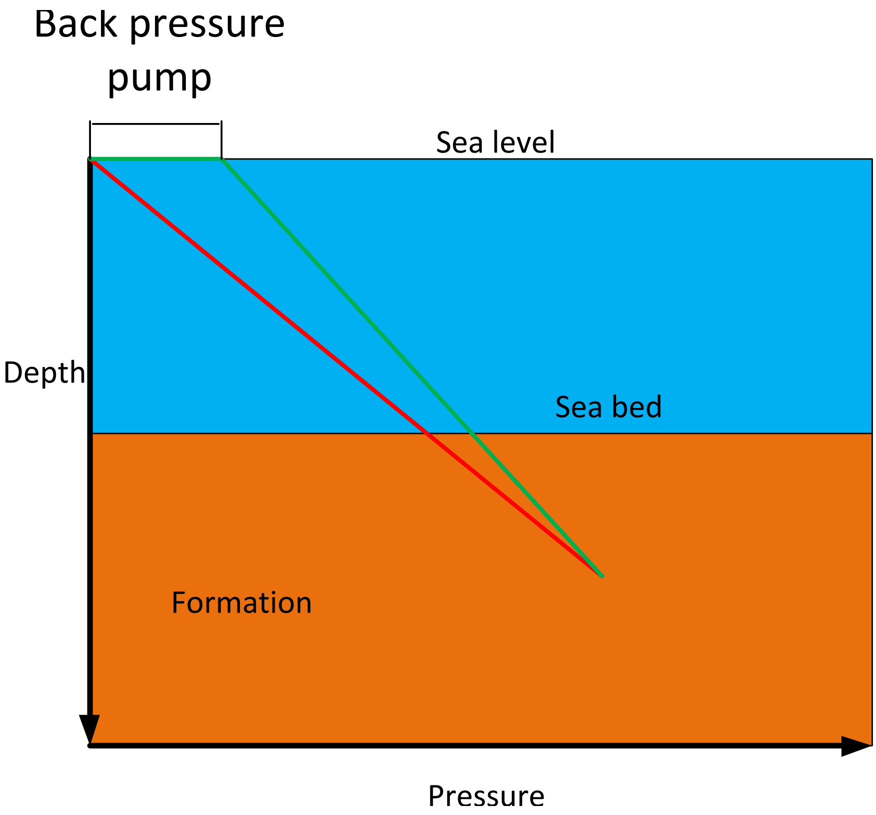

Figure 3.8: Pressure gradient for constant bottom hole pressure.[22]

3.2.3 Pressurized mud cap

Pressurized mud cap drilling can be used in placed where it is difficult to maintain circulation. Fractured formation and depletion can cause circulation problems [4].

In mud cap drilling there are no returns to surface and all cuttings are transported into the formation, such that there is a static column with mud in annulus. Since there are no return to surface, sacrificial mud is used for drilling, if PMC is to be economical feasible. RCD is necessary for the system to pressurize annulus.

Figure 3.9 shows a flow chart for PMC drilling is presented is shows that mud are pumped on from the mid pump and into the formation.

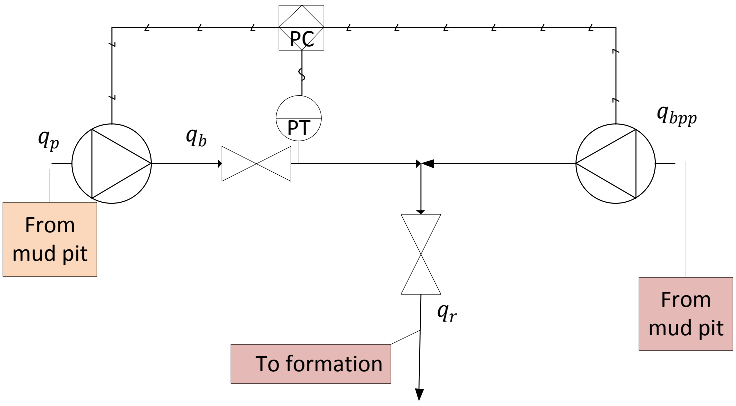

Figure 3.9: Flow schematic for pressurized mud cap method.[8]

When compared to CBHP-drilling the pressure gradient for PMC is different. In figure 3.10 pressure gradient in PMC is presented. As can be seen the pressure gradient are dual but the where the deepest fluid have a steeper decent.

3.2.4 Dual gradient method

Dual gradient drilling (DGD) is a very young technology. The method is developed for deep water prospects where there can be a problem that a marine riser is necessary. There are two problems with using a marine riser in deep water.

- Logistic: There is a huge cost to transport and storage of a long marine riser.
- Narrow pressure window: The difference in gradient for mud and seawater narrows the drillable pressure window increasing casing points.

In addition is that target depth tends to be deeper below the mud line in deep waters. The pressure gradient vs depth have a different curve that for CBHP and PMC. In figure 3.11 the difference in pressure gradient vs. conventional drilling is presented.

There are two concepts in DGD with or without a riser.

When drilling without a riser. Here a subsea pump is used to transport mud to surface for treatment. A suction module is attached to the wellhead. The drill string enters the well through the suction module. The subsea pump is connected to the suction module.

In DGD with riser there is a mud cap in the riser such that a suction head is created and measured to control the subsea mud pump. The set point for suction pressure allows for variable head in the riser. DGD with riser advantages is:

1. It permits drilling with higher density mud than in conventional drilling
2. Improved control of BHP and ECD.

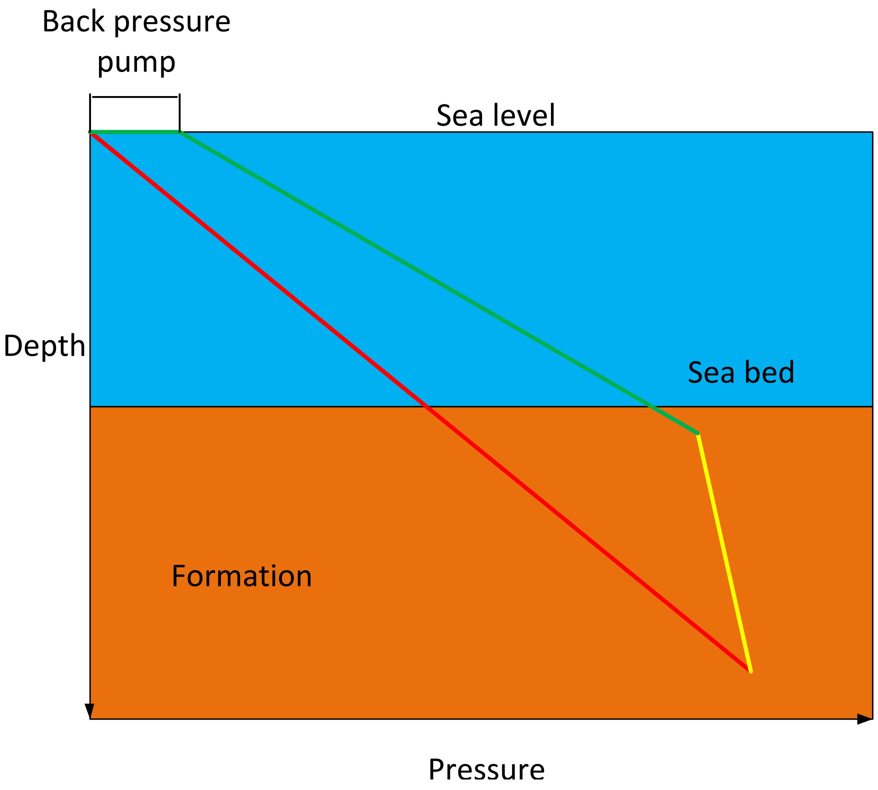

Figure 3.10: Pressure gradient for pressurized mud-cap drilling.[22]

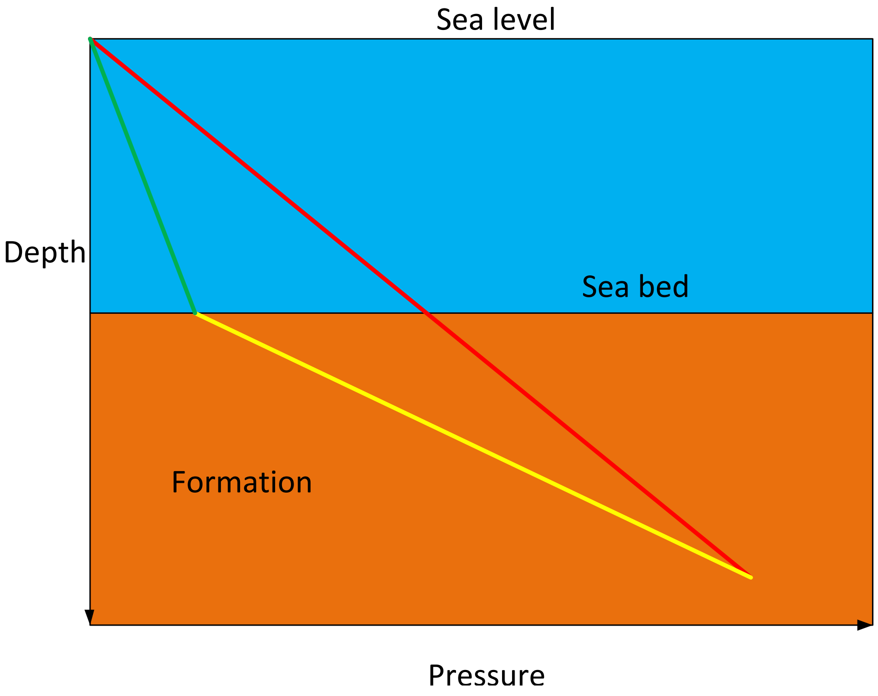

Figure 3.11: Pressure gradient for dual gradient drilling.(Insert reference here)

3. Extends casing depths
4. Increased maneuvering in narrow pressure window.

Since the mud from annulus has to be pumped from seabed up to the drilling vessel a cutting processor is necessary. This processor crushes larger cuttings such that they can be handled by the subsea mud pump.

In DGD there is an active U-tube effect. This effect is like a manometer. In conventional drilling it is balanced since the same hydrostatic head in drill string and annulus is equal. In dual gradient drilling this is not true since the hydrostatic head in drill pipe is larger than in annulus. There are six factors that influence U-tube effect.

- Water depth
- Mud density
- Mud viscosity
- Inside diameter of drill string
- Restrictions in drill string
- Depth below mud-line

The main factors that influence U-tub effect is water depth and mud density. In figure 3.12 the difference in u-tube head is illustrated.

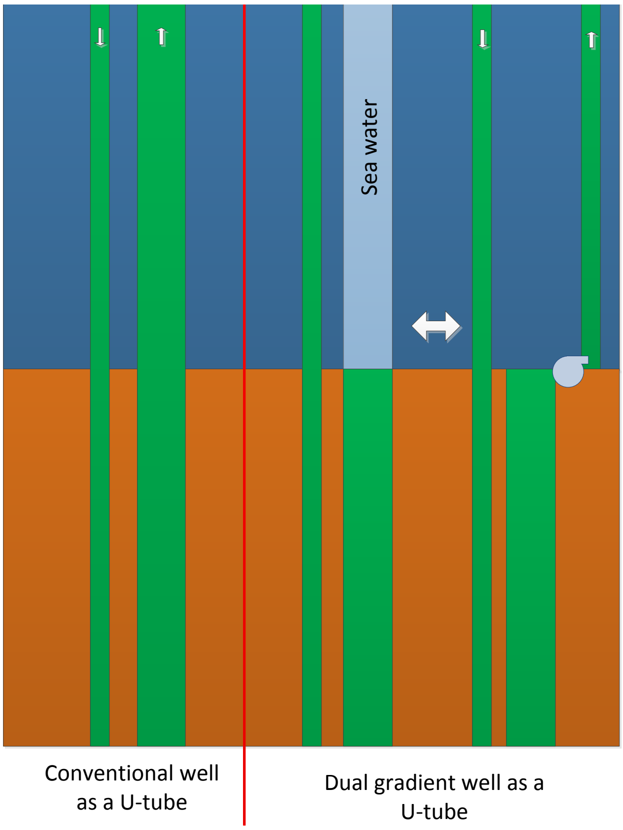

Figure 3.12: U-tube effect and head difference between conventional drilling and DGD.[4]

For DGD with riser the following figure 3.13 illustrates how flow can be in in the system.

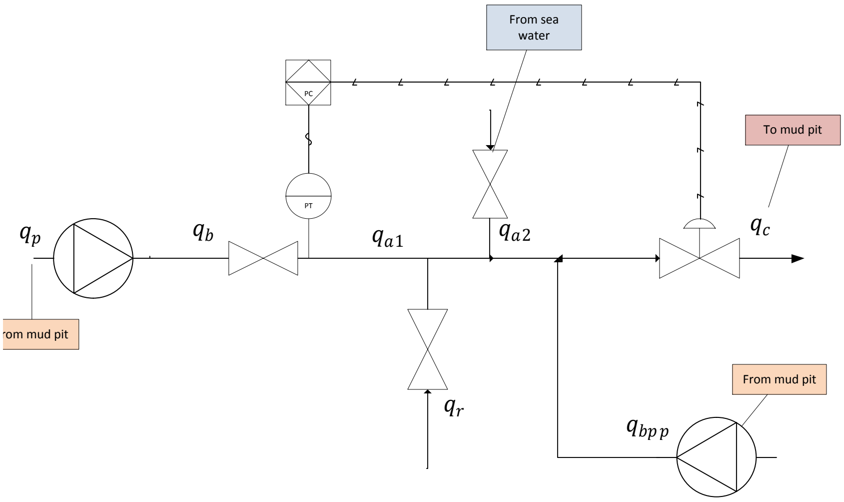

Figure 3.13: Flow schematic for dual gradient method.(Insert reference here)

3.2.5 HSE

In some occasions annulus is pressurized for reducing risk for HSE concerns. Mud return is closed to atmosphere to prevent risk of mud gas to trigger a dangerous explosion. This is done when drilling is done on platforms where production is done simultaneously. Thus, production stop because of gas release can be very expensive. There can also be regulations which requires that if mud gas is released to atmosphere authorities are alerted [17].

3.3 UBD drilling

Under balanced drilling (UBD) is by International association for drilling contractors(IADC) defined as [3]

Drilling with the hydrostatic head of the drilling fluid intentionally designed to be lower than the pressure of the formations being drilled. The hydrostatic head of the fluid may naturally be less than the formation pressure, or it can be induced. The induced state may be created by adding natural gas, nitrogen or air to the liquid phase of the drilling fluid. Whether the underbalanced status is induced or normal, the result may be an influx of formation fluids which must be circulated from the well and controlled at surface.

Before the BOP was invented, to hinder blowouts, all wells were drilled under balanced.

Advantaged for drilling under balanced is:

- Minimizing pressure-related drilling problems
- Maximizing hydrocarbon recovery
- Characterize the reservoir

Pressure related drilling problems is: Differential sticking, fluid loss and increased penetration rate. Differential sticking can lead to stuck pipe. Fluid loss does not occur in UBD and thus fractures on the reservoir is protected from outflux damage. Penetration rate is usually increased but other factors may limit this effect. A connection takes more time when UBD is used, since handling of hydrocarbons at surface eliminates time gains from increased ROP.

Hydrocarbon recovery is increased since no drilling fluid flows into the formation. On a long time horizon UBD wells performs better than conventional wells and have slower decline of hydrocarbon production. This effect is not significant on a short production horizon.

Reservoir characterization may favor UBD because of reservoir profile, fractures and the possibility to steer the drilling into more favorable production parts of the reservoir.

Under balanced drilling is in many ways similar to MPD, but this technique is used for fields which is severely depleted and where mud loss is a significant problem. If conventional drilling is on the

Because UBD invites influx it is necessary with special equipment to handle the influx fluid

3.4 Challenges and potential with automation of MPD

Automation of drilling systems have continuously been improved since the start if drilling in the 19th century. Most of the automation have been done on topside equipment, in recent years automation have also been done for down hole equipment.

In 2007 Alfred W. Eustes III wrote a paper on the evolution of drilling [26] here some of the most important "game changers" in the oil industry is presented. These are the most important changes on how drilling is performed and presents and some of the most important technology where automation has been introduced to increase safety and reduce risk. In *Control requirements for high-end automation MPD operations* [14] Godhavn presents some important requirements if automated drilling should successfully be the standard way of drilling.

There are several fields in automation and industrial IT which could contribute to increase drilling automation. These fields are interesting for reduce risk, cost and improve regulation.

- Robotics
- Instrumentation
- Control algorithms
- Parameter estimation
- Dynamic models

3.4.1 Robotics

Robotics has already been successfully used in several drilling operations. Tasks that is done by automatic are

- Tripping,
- Topside operations, connections, circulation; reaming and friction test
- On bottom drilling: Optimize drilling efficiency; ROP and equipment lifetime.

Several of the tasks done topside is already automated, mostly because the work was dangerous for humans. The automation systems topside are usually divided into several different subsystems which may have little interaction with each other.

3.4.2 Instrumentation

Instrumentation is adapted to the demands necessary for today's manual drilling where high quality of the measurement is not necessary. If fully automated drilling are to be achieved there have to be some significant changes in the quality of some instrumentations measurements.

Pressure while drilling (PWD) is one example where measurements have to be more accurate, precise and have shorter sampling interval. One alternative to PWD is the wired drill pipe (WDP) which allows for two way communication continuously [7].

The reliability on some of the equipment used in drilling would have meant ruination in less cost efficient industries. Pumps, valves, sensors, communication and logging could have much better reliability if there had been a greater focus on increased quality. successful automation is dependent on high quality on instrumentation.

3.4.3 Control algorithms

There are several different control algorithms that can be used for automatic control. Most of the controllers used in the industry are PID controllers. It is a simple controller which is easy to tune for a sufficient problem solution. There is also several different methods for tuning the PID controller. Some useful tuning methods are

- Ziegler & Nicols method
- Skogestads method
- Good gain

There are many other control laws that can be used, which can be better fitted to improve control performance:

- H-infinity
- Linear Quadratic control (LQC)
- Model predictive control (MPC)
- Back-stepping controller
- Feedback linearisation
- Sliding mode
- Nonlinear model predictive control (NMPC)

The three first controllers above are based on linear systems theory, while the four others are based on nonlinear systems theory.

3.4.4 Parameter estimation

In some model all states are not available for measurement. In these cases it is necessary to estimate their value. Estimation of parameters can be done with several different methods. Observers and Kalman filters are those most used. Observers and Kalman filters are derived from linear systems theory, but there exists several nonlinear observer and Kalman filter algorithms which have been developed. These estimators are dependent on a process model. The estimate quality is dependent on how good the model represents the real process. A bad model may give useless estimates.

3.4.5 Dynamic models

Simulation of dynamic models has solved several problems in different industries which could have been fatal if they had not been detected during simulation. Testing of control algorithms and estimators with simulation has reduced start-up time in several projects.

3.5 Faults in MPD

When drilling many different problems can occur. Some are more dangerous than others. Some of the most dangerous failures is:

1. Blow-out
2. Power loss
3. Stuck pipe
4. Twist off

Other problems that can occur:

- Kick
- Loss,Loss- kick
- Blocked choke
- Loss of pressure measurement
- Loss of flow measurement
- Loss of back pressure pump
- Poor quality on down hole pressure measurement
- Drillpipe washout
- Annulus washout
- Mud pack-off
- Differential stuck pipe
- Lost circulation
- Annulus ballooning
- Reactive formation (Swelling shale)

There are several other problems which can occur but these are the most common drilling problem related to NPT.

Kick

A kick is an unintentional influx of fluid into annulus [4]. Influx of fluid is the result from annulus pressure below pore pressure. Kicks are usually stopped by injecting heavy mud into the well. Either through the drillpipe or through a kill line which inject mud directly into annulus.

If the driller doesn't manage to control the kick it is called a blowout. There have been several accidents related to blowouts during drilling history. One of the most recent and known is the Deepwater horizon incident i the Gulf of Mexico. To handle blowouts a BOP is installed at the well head. BOP function is described in chapter 3.1.5.

3.5.1 Loss, Loss-kick

Loss is when the mud is lost because the annulus pressure is higher than the overburden pressure and drilling fluid is outfluxing from annulus [5]. To solve this less dense mud is circulated into the well to stabilize the pressure such that there is no influx of outflux.

The loss-kick situation comes from when the mud weight is decreased such that a kick is induced because of the loss situation. Drilling fluid can be very costly so loss situation can have huge impact on the profit from a well if the loss is too severe the well can be abandoned.

PMC is a method which is often used in wells where loss is a problem.

3.5.2 Blocked valve

When using a choke valve the driller is dependent on the valve to be operational at all time. Cuttings from annulus can sometimes get stuck in the valve such that the control mechanism in the choke gets stuck. If the valve is stuck in closed position the driller cannot control the pressure in the well and the well circulation halts, then drilling has to stop until the choke is repaired.

Normally there are several choke valves installed in parallel for redundancy. In this way drilling can resume because there are a backup ready such that the damaged valve can be bypassed and repaired.

3.5.3 Power loss

Power loss is a severe problem. This since it results in power loss of all applications on the rig also eventually safety system. If this happens the safety system is connected to a uninterruptable power supply (UPS) which have sufficient power to set the well in a safe state.

3.5.4 Loss of pressure measurement

If pressure measurement is lost the driller is blind to what happens in the well. Loss of pressure can indicate that simply the connection to the sensor is lost, sensor is broken or that some fault has happen that leads to measurement error.

In MPD the PWD is essential for updating set point of choke pressure and hydraulic model. There is several other pressure measurement that is done to control the well. Sudden changes in pump pressure and back pump pressure can also indicate that something is not right.

3.5.5 Loss of flow measurement

Flow measurement is the fastest way to detect a well kick [8]. If there is large deviation in fluid density of flow in and out of the well this can indicate a kick or that drilling fluid is lost.

3.5.6 Loss of back pressure pump

Lost back pressure pump results in lost back pressure during shut in and drill string handling. If the pressure window is small this means that the choke valve possibly can't close fast enough to trap sufficient pressure in annulus for a safe shut in.

3.5.7 Poor quality on down hole pressure measurement

If the quality of PWD measurement is bad this can lead to wrong set point on the choke. The down hole pressure is very sensitive for small changes in choke pressure such that if there is a small pressure margin measurement has to be accurate if the down hole pressure to be controlled accurate [15].

3.5.8 Drillpipe washout

Drill pipe washout is a problem when using old drill pipes. It results from corrosion on the treads such that mud flows from drill pipe to annulus before it has reached the drill bit, this lead to inefficient drill bit cleaning, slower ROP and reduced BHP. If washout is detected in a drill pipe, it should be scraped, because washout is a strong indicator that drill string is about to twist off [18].

3.5.9 Annulus washout

Annulus washout is where formation sediments on the annulus wall are washed out with the drilling fluid and cuttings. This leads to annulus volume expands unintentionally. The severity of a washout depends on circulation speed of the drilling fluid. If washout is detected the circulation speed has to be reduced to minimize washout.

3.5.10 Mud pack-off

Mud pack-off happens if the drilling fluid doesn't transports enough cuttings. Then cuttings packs around the drill-bit and pressure increase until it dissolves the packed sediment. The pressure before the packed cuttings dissolve can in many situation be significantly higher that the fracture pressure such that severe formation damage can results from pack-off [].

3.5.11 Stuck pipe

There are several causes for stuck pipe [12]. Pack-off is one situation which could result in stuck pipe. Other situations are differential sticking, reactive formation and hole geometry.

Differential sticking is the most common situation to cause stuck pipe. It results from the pressure difference in pore pressure and annulus pressure sucks the pipe such that it sticks to the annulus wall.

3.5.12 Twist off

Twist off happens if the torque applied to the drill string becomes too high. To avoid this estimation of friction can be done. Twist off is usually a result from equipment fatigue. Drill string washout is a strong indicator that twist off soon may happen [18].

3.5.13 Annulus ballooning

Ballooning happens in high temperature wells when circulation is stopped [20]. Heat transfer expands the mud such that the mud volume is increased. This can lead to a seemingly change in flow though the choke later when circulation is resumed.

3.5.14 Reactive formation

Reactive formation like shale responds to different types of drilling fluid by swelling and thus can close the annulus such that the string is stuck [12] [25] .

Chapter 4

Model for fault tolerant control of automatic MPD

This chapter presents a FTC system for MPD. The chapter start with define a nominal model and controller for normal operation. Normal operation switches between circulation during drillng and static state when adding pipe to the well.

There are several different faults that can occur during MPD. Some of them are easy to detect while others very difficult. Before a FTC system can be implemented the faults have to be examined and classified, such that it can be identified if the different faults are diagnosable with the nominal model and if they these fault does not propagate to failures which the safety system handle.

Then the architecture of the system is defined. MPD and conventional drilling can be described with different subsystems, such that observation of faults and correction of the faults is not necessarily done by changing the same system, thus it is a decentralized diagnosis system if there is not implemented a coordination of the faults.

At last control redesign is described. Here there controllers for the different fault situations are described and specifications necessary when switching from a faultless system to a faulty system.

4.1 System architectures for automatic MPD

The architecture for drilling with MPD is decided by what equipment which is used.

In chapter 3 well drilling was described by the subsystems necessary for drilling. Some of these systems are necessary for conventional and MPD. Here CBHP drilling is considered.

In Managed pressure drilling [4] the necessary equipment for CBHD is presented

- Choke manifold
- Back pressure pump
- Integrated pressure manager
- Hydraulics model

This suggests that the difference from conventional is adding a choke and back pressure as physical changes, pressure management and hydraulics model are necessary for controlling the system.

Since FTC is complicated to implement it is preferable to reduce the hydraulic model to minimum. This suggests the use of a coordinated diagnosis system where faults are detected in the systems where they are observable and communicated to other subsystems using the fault diagnose.

4.2 Nominal model and controller for MPD

This thesis uses a simple hydraulic model which are used for adaptive control of the BHP of a well and is used as a model for CBHP [6].

During drilling there are two different dynamic situations which is interesting:

- Drilling; Here the circulation system is running
- Shut in; Circulation is halted as a new connection is made.

From a FTC point of view these two cases represents two different dynamical systems where the first case can be behavior $\mathcal{B}_{01}$ and the second case $\mathcal{B}_{02}$ since the reason for the circulation stop is that the system is out of reach for drilling further and thus have to add length to the drill string.

From here on the behavior for normal circulation is denoted $\mathcal{B}_{01}$ and for the static case $\mathcal{B}_{02}$. Behavior $\mathcal{B}_{01}$ is explored first then $\mathcal{B}_{02}$.

4.2.1 Well dynamic during drilling

First behavior $\mathcal{B}_{01}$

$$\begin{aligned} \dot{p_p} &= \tfrac{\beta_d}{V_b}(q_p - q_b) \\ \dot{p_c} &= \tfrac{\beta_a}{V_a}(q_b + q_r + q_{bpp} - q_c) \\ \dot{q_b} &= \tfrac{1}{M_d+M_a}(p_{bp} - p_{ba}) \end{aligned} \tag{4.1}$$

The first equation describes the mud pump pressure p_p, the second equation is the choke pressure p_c and the third is the mass flow through the drill bit. The model parameters are described in table 3.1. M_d and M_a is mass in drill pipe and annulus, which can be simplified to $M_d + M_a = M$. The parametrization for p_{bp} and p_{ba} used in this thesis is

$$\begin{aligned} p_{bp} &= p_p - F_p(q) + G_p(\rho_p, h) = p_p - F_p q^2 + \rho_p g h \\ p_{ba} &= p_p + F_a(q) + G_a(\rho_a, h) = p_c + F_a q^2 + \rho_a g h \end{aligned} \tag{4.2}$$

The measurement equation for down hole pressure can be described with the equation

$$p_d h = p_c + F_a(q) + G_a(\rho, h) \tag{4.3}$$

Where $p_d h$ is down hole pressure, $G_a(\rho)$ is the gravity pressure loss in annulus and $F_a(q)$ is the frictional pressure loss in annulus.

A simple parametrization for $G_a(\rho)$ is

$$G_a(\rho) = \rho_a g h \tag{4.4}$$

while a simple parametrization for $F_a(q)$ is

$$F_a(q) = C_a q^2 \tag{4.5}$$

When using FTC it is practical to set the system up on a standardized form.

$$\begin{aligned} \dot{x} &= Ax + Bu + v \\ y &= Cx + w \end{aligned} \tag{4.6}$$

Where x is defined as

$$x := \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} p_p \\ p_c \\ q_b \end{bmatrix} \tag{4.7}$$

4.2.2 Well dynamic during shut in

During shut in there are no flow from the mud pump such that there are no flow through the drill bit, but since the BHP p_b is dependent on the pressure p_c the pressure can still be managed. By using the backpressure pump to increase the flow through the choke the pressure increase and thus the BHP p_b. The model is in then

$$\begin{aligned} \dot{p_p} &= 0 \\ \dot{p_c} &= \tfrac{\beta_a}{V_a}(q_{bpp} - q_c) \\ \dot{q_b} &= 0 \end{aligned} \tag{4.8}$$

and measurement is changed to

$$y(t) = p_c + \rho_a gh \tag{4.9}$$

4.2.3 Measurement

Measurements during circulation, can use PWD measurements; here it is assumed that the measurement is updated rapidly such that the BHP measurement can be used directly.

During shut in this is not the case as PWD is dependent on circulation for transmitting. Thus the last measurement on the choke before shut in is a good guestimate for selecting a reference value to controlling BHP.

The measurement equation are then

$$y = \begin{bmatrix} p_c \\ p_c + \rho gh + f_a q^2 \end{bmatrix} \tag{4.10}$$

4.2.4 Actuators

The actuators in 4.1 are the mud pump q_p, the choke valve q_c, and backpressure pump q_{bpp}. The reservoir flow can q_r can reasonably be assumed to be zero when the wells pressure balance is correct. Assuming the mud pump flow is regulated to achieve a specified circulation of mud and thus is not influenced by the well pressure it can be assumed that the mud pump q_p is a measured disturbance in the system. The choke flow is nonlinear with respect to the control signal u_c such that

$$q_c = C_v u_c \frac{\sqrt{p_c}}{\rho_a} \tag{4.11}$$

By using the input vector $u(t)$ where all elements have the same physical dimension that gives:

$$u = \begin{bmatrix} q_c \\ q_{bpp} \end{bmatrix} \tag{4.12}$$

Where there is a constraint on $q_{bpp} > 0$ during normal operation. The input matrix is B is then

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \dfrac{\beta_a}{V_a} & -\dfrac{\beta_a}{V_a} \\ 0 & 0 & 0 \end{bmatrix} \tag{4.13}$$

4.2.5 Control

The system is a multiple input single output (MISO) system thus there is a direction involved to control the system to desired value [24]. Fortunately here the inputs are in different directions such that there is only necessary to find a control law where the system converge to the desired reference value.

Locking the choke in a constant position makes it simple to regulate the down hole pressure and a PI-controller can be used to control the system.

Since there are two different measurement used there is also two different control errors which can be used

$$\begin{aligned} e_1(t) &:= y_{ref1} - p_c \\ e_2(t) &:= y_{ref2} - p_{BH} \end{aligned} \tag{4.14}$$

Four different controllers are used during normal operation.

$$\begin{aligned} u_{bpp11}(k) &= u_{bpp11}(k-1)u_{bpp11}(k-1) + Kp_{bpp11}(e_1(k) - e_1(k-1) + \frac{h}{T_{ibpp11}}e_1(k)) \\ u_{bpp12}(k) &= u_{bpp12}(k-1)u_{bpp12}(k-1) + Kp_{bpp12}(e_2(k) - e_2(k-1) + \frac{h}{T_{ibpp12}}e_2(k)) \\ u_{c1}(k) &= u_{c1}(k-1) + Kp_{c1}(e_1(k) - e_1(k-1) + \frac{h}{T_{ic1}}e_1(k)) \\ u_{c2}(k) &= u_{c2}(k-1) + Kp_{c2}u_{c2}(k-1)(e_2(k) - e_2(k-1) + \frac{h}{T_{ic2}}e_2(k)) \end{aligned} \tag{4.15}$$

The controllers $u_{bpp1}(k)$ and $u_{c1}(k)$ are used for behavior $\mathcal{B}_{01}$ while $u_{bpp2}(k)$ and $u_{c2}(k)$ are is used for behavior $\mathcal{B}_{02}$.

4.2.6 Stability

The system can be shown to be internal stable by assuming that $u(t) = 0$ and the disturbance $q_p = 0$ such that the system is described as

$$\begin{aligned} &\dot{p_p} = \frac{\beta_d}{V_b}(-q_b) \\ &\dot{p_c} = \frac{\beta_a}{V_a}(q_b) \\ &\dot{q_b} = \frac{1}{M_d+M_a}(p_p + \rho_p gh - p_c + \rho_a gh) \end{aligned} \tag{4.16}$$

Where $q_b = 0$, thus one can assume that $\rho_b = \rho_a$ since there are no drilling when the flow q_b is zero. such that the system states is

$$\begin{aligned} &\dot{p_p} = 0 \\ &\dot{p_c} = 0 \\ &\dot{q_b} = 0 \end{aligned} \tag{4.17}$$

4.3 Fault classification

Fault in a drilling system can have very different consequences and therefore there is need to look into which faults where there would be most gained to use FTC.

In table 4.1 the faults listed in chapter 3 are listed and which systems the faults changes the system and the fault type. Fault type is based on the theory from chapter 2 where the faults types are defined as

- AF- Additive fault
- MF- Multiplicative fault

Table 4.1: Fault classification

Fault	**Fault identifying system**	**Fault type**	**System behaviour**
Kick	Circulation system	AF	Fluid influx
Blowout	Safety system	Fail	Fluid influx
Loss	Circulation system	AF	Fluid outflux
Blocked valve	Circulation system	AF	Actuator failure
Power loss	Safety system	Fail	Safe shut down
Loss of PWD	Circulation system	AF	Sensor failure
Loss of Bp pump	Circulation system	Fail	Safety system/ Actuator fault
Poor quality on PWD	Circulation system	AF	sensor fault
Drill pipe washout	Circulation system	MF/AF	BHP and flow reduced
Annulus washout	Circulation system	MF	Volume V_a is increased
Mud pack-off	Circulation system/ Mud mixing	MF	Pressure p_b increase while flow does not occur
Stuck pipe	Hoisting system	MF/AF	Several reasons
Twist off	Rotary system		Increased in torque
Annulus ballooning	Volume estimation	MF	volume V_a is changed
Reactive formation	Volume estimation	MF	volume V_a is decreased

- Fail-Failure

Column one names the fault, column two is the system where is is probably easiest to identify the fault and column three is the fault classification and column four is how the systems behavior changes. To detect the fault this behavior must be observed.

As can be seen from table 4.1 there are several different fault that can occur which can be observed when simulating the circulation system. Most of the faults are directly related to the system parameters and can be difficult to identify and compensate for.

There are some fault that are related to actuators, Blocked vale, and for sensors are loss of PWD. These faults is investigated further since here the simplifications form chapter 2 can be applied.

4.3.1 Blocked choke

The choke valve can sometimes get blocked by cuttings such that there is no flow through the valve. The choke valve is usually physical redundant where more than one choke is installed in parallel. Even with this redundancy it is not always sufficient to keep the system running. Thus analytical redundancy can be used in addition to increase regularity. When analytical redundancy is used it changes the systems dynamic as it alters how actuators or sensors are used. Therefore a new model is necessary when simulating the behavior when the analytical alternative is used.

An alternative for a blocked choke is to use the back pressure pump alone to control the BHP. Associated with this alternative is new a behavior which is called $\mathcal{B}_{11}$ for the behavior during circulation and behavior $\mathcal{B}_{12}$ during shut in. The model for $\mathcal{B}_{11}$ is then

$$\begin{aligned}\dot{p_p} &= \tfrac{\beta_d}{V_b}(q_p - q_b)\\ \dot{p_c} &= \tfrac{\beta_a}{V_a}(q_b + q_r + q_{bpp})\\ \dot{q_b} &= \tfrac{1}{M_d+M_a}(p_{bp} - p_{ba})\end{aligned} \tag{4.18}$$

Be aware that here there are no constraints on q_{bpp}.

For behavior $\mathcal{B}_{12}$ the new model is:

$$\begin{aligned} \dot{p_p} &= 0 \\ \dot{p_c} &= \tfrac{\beta_a}{V_a}(q_{bpp}) \\ \dot{q_b} &= 0 \end{aligned} \tag{4.19}$$

As can be seen from (4.19) the pressure at the choke is now only dependent on backpressure flow.

4.3.2 Loss of PWD

BHP measurement can only be done during circulation. It is therefore not possible to use this measurement during shut in to regulate the pressure. Since the BHP is regulated with the choke or the back pressure pump the pressure measurement over the choke can be used instead of PWD. The range of PWD measurement and the choke pressure is different and has different sensitivity and it is therefore not easy to just change from one to the other.

The BHP is measured by using PWD. This is a pulse transmitted via the drill string mud which request data from the bottom hole assembly. The BHP measurement can is used in a very harsh environment and in a huge measurement range. Thus the precision of the PWD measurement can be poor; another point is that the sampling interval is very long, around 20-30 seconds. Since the measurement value is communicated via the drill string mud, BHP cannot be updated during shut in. Normally the choke pressure is used for control during drilling and shut in.

A technology where BHP is always available is wired drill pipe telemetry system (WDP). It provides high bandwidth; two way communication and pressure measurements along the whole drill pipe [16].

In the simulation it is assumed that the PWD measurement is good and that the BHP updated at each sample. Thus the controllers use different measurements depending on whether there is circulation or not i the system. This is done in this simulation to simplify the simulation as the interesting problem is to see if it is possible to only use back pressure pump to control pressure.

4.4 Model matching FTC for automatic MPD system

Since a nominal plant and a faulty behavior are presented the two can be combined into one system by using FTC. Model matching is used as the architecture for the fault tolerant control system. The program procedure is based on figure 2.1. The simulation loop can be seen in figure 4.1. The first block in figure 4.1 shows that a controller is selected based in a fault situation. In the next block the input is calculated. In the next block the plant calculate next for next time step based on controller input and fault generation which is used for simulation of faults. In the last block a diagnosis is made based on system behavior.

4.4.1 Fault simulation

The faulty model has different dynamics than the nominal model. To simulate the faulty behavior $\mathcal{B}_f$ a new dynamic model that represents this fault have to be developed. Faults that are easy to simulate are actuator failure and sensor failure. For actuator fault this can be done by setting the actuator value to zero, while the actuators control value is nonzero.

To simulate a blocked choke B in equation 4.13 can be altered such that

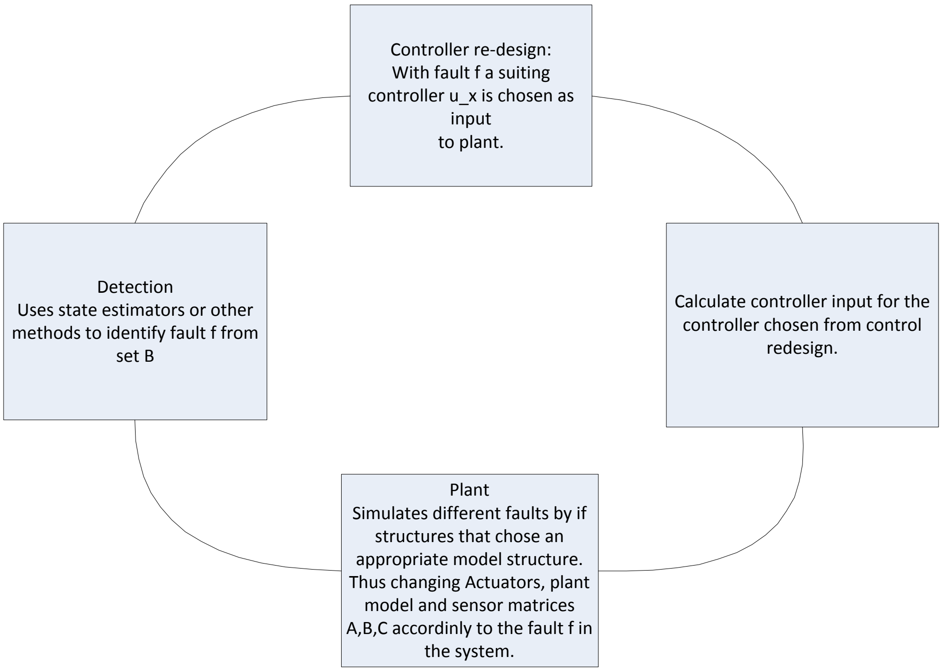

Figure 4.1: Program procedure.

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\beta_a}{V_a} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4.20}$$

To show that this will work the pseudo inverse method can be used. By using the relation 2.19 matrix 4.13 and 4.20 have equal rank.

Actuator faults

Actuator faults can have severe impact on a control systems performance. In MPD there are several actuators that are used for controlling the system: Mud pump, back pressure pump and choke valve.

The mud pump is necessary for the system's circulation, thus a failure here leads to a system failure. The back pressure pump and the choke valve are used for controlling the BHP, one of them has to handle the return flow from annulus, such that the system fails if both fails.

From an analytical viewpoint there is a possibility for using the back pressure pump alone if the choke fails would work. While if the back pressure pump fails there are a risk that pressure during shut in is reduced such that there is influx into annulus. The reason for this is that the choke is passive since it cannot add mud to increase the pressure. While the back pressure pump is active and can increase pressure in annulus.

Under nominal conditions $\mathcal{B}_{01}$ and $\mathcal{B}_{02}$ the back pressure pump adds mud such that q is always positive. During $\mathcal{B}_{01}$ which is drilling the back pressure pump is not needed and $q_{bpp} = 0$, but during shut in the systems behavior changes and the increased flow from q_{bpp} to q_c increases the choke pressure which indirect increases the BHP.

If there is a fault in the choke such that it is blocked completely, the dynamic have changed such that the back pressure pump has to be used instead of the choke.

Table 4.2: Controllers used in simulation of fault tolerant control

Controller	**Operational state**	**Behaviour**
u_{c11}	Circulation	Normal
u_{c12}	Static	Normal
u_{bpp11}	Circulation	Normal
u_{bpp12}	Static	Normal
u_{bpp21}	Circulation	Choke failure
u_{bpp22}	Static	Choke failure

During shut, in the pump has to be able to have both negative and positive direction. If the pump only pumps mud out of the system pressure can become to low, and the opposite if the mud only pumps into the system.

4.4.2 Fault diagnosis

It is assumed that the detection and estimation is done immediately such that the fault status of the system is always known.

The diagnosis can be done with by compare the plant input and output with a state observer that then compare the input u and output y according to a nominal plant model. If there is a residue there may be a fault in the system and the diagnosis output a different f to the control re-designer to correct the system.

4.4.3 Control

The system changes during circulation and static state there are need for different controllers, because of the different dynamic when changing from one to the other. In addition the fault alters the dynamic such that there is need for individual controllers for each fault case.

There is one control for each input signal. Therefore there are four controllers used during normal operation while there are two controllers used during fault.

The controllers are presented in table 4.2.

There are several different methods for controlling the down hole pressure in a well. The most used is the PI-controller, all though it has some limitations for its use. The controllers are based on PI(D) control and are on velocity/incremental form.

The PI controllers used during normal operation is described in (4.15). While for the faulty system 4.18 the controller which is used is

$$u_{bpp21}(k) = u_{bpp21}(k-1)u_{bpp21}(k-1) + K_{p21}u_{bpp21}(k-1)(e_1(k) - e_1(k-1) + \frac{h}{T_{i21}}e_1(k)) \tag{4.21}$$

While for 4.19 the controller is

$$u_{bpp22}(k) = u_{bpp22}(k-1) + K_{p22}(e_2(k) - e_2(k-1) + \frac{h}{T_{i22}}e_2(k)) \tag{4.22}$$

There are several different implementations and alternative algorithms which can be used to exploit favorable nonlinearities in the system such that better convergence is achieved.

The back pressure controllers for static state uses a nonlinear initialization the reason for this comes from simulation and will be discussed later.

PI(D)-controller tuning

PI controller is the most used controller in the world and is easy to use. There is several different methods for tuning this controller, the difference is in how the system response to set-point changes and disturbances. The most important tuning rules is Ziegler-Nichols, IMC PID-tuning, Smith and Corripo and Skogestads method [23].

Ziegler-Nichols tuning method gives a aggressive tuning, have good disturbance response for integrating processes, but it have poor performance for processes with dominant delay. IMC-tuning rule have poor performance for integrating processes, but have good responses for set-point change. Skogestads method is model based where the system is linearized to a second of first order process with delay.

The good gain method has been used. It is a very simple method for tuning a PI controller.

The method uses a guestimate for the controller gain. Then finds a integral time which fits, to improve the controller performance.

4.4.4 Controller redesign

The control redesign is a discrete selector that chooses the controllers to used on the plant based on the system diagnose f.

The control re-designer have a value f from the diagnosis block as an input. From this f an appropriate controller is selected to handle the plant appropriately according to the plant fault state f.

4.4.5 Simulation parameters

Here the parameters used for simulation is presented.

Table 4.3: Model parameters used

parameter	**value**	**Description**
h	0.2	sample time
β_a	5000	bulk modulus annulus
β_d	15000	bulk modulus pipe
V_a	140.8907	Volume annulus
V_d	37.7059	Volume pipe
M_a	1600	Mass annulus
M_d	6000	Mass pipe
depth	1826	Well depth
g	9.81	mass acceleration

Initial values

Table 4.4: Initial values

parameter	**value**	**Description**
q_p	0.0339	Mud pump flow
q_c	0.1094	Choke flow
q_{bpp}	0.107	Backpressure pump flow
p_p	188.1	Mud pump pressure
p_c	14.5	Choke pressure

Initial values used in simulation

Table 4.5: Controller parameters

Controller	**Kp**	**Ti**
u_{c11}	-0.001	0.02
u_{c12}	-0.001	0.06
u_{bpp11}	0.0001	0.95
u_{bpp12}	0.007	1
u_{bpp21}	0.04	0.9
u_{bpp22}	0.000001	80

Chapter 5

Simulation of fault tolerant control

This chapter presents the simulation results. There have been done several different test cases to test the system as progress has been done.

5.1 Simulation of normal operation

First is a simulation of normal operation.

In figure 5.1 the bottomhole pressure is shown. The blue plot is the simulated value form using the nominal controller as input. The other plots are data with annulus pressure from a real well. The real data is based on a standard drilling sequence which contains data on most equipment used during drilling.

The cyan color plot is real data and is the bit pressure from a well where the hydraulic model has been used. The pink color are modeled annulus pressure, dotted pink is annulus pressure.

As can be seen there is very huge difference in the simulated and real data value. The simulated value has small deviation from the set point value which is 240 bar.

Figure 5.2 shows the systems states values p_p, p_c and q_b.

The blue data is the simulated value, while the red is real data. There are some deviations in the pressure measurement for the choke and standpipe pressure.

The flow q_b varies during the simulation. The flow is zero during a shut in, where new drill pipe is added for further drilling.

Figure 5.3 shows the control input and the output values.

The upper plots are the bottom hole pressure to the left and choke pressure to the right. These are the systems output values used as feedback to the controller.

The input plot is the lower plots and are the backpressure pump and choke valve. During shut in the choke valve closes and traps the pressure inside the annulus.

5.2 Simulation with known fault

The simulation with fault are a simulation where there choke are blocked during the whole simulation. Thus the only actuator controlling this is the backpressure pump.

In figure 5.4 the BHP p_b is shown.

The blue plot is the simulated value form using the fault controller as input. The other plots are data with annulus pressure from a real well. The data bases on a standard drilling sequence which contains data on most equipment used during drilling.

The cyan color plot is real data and is the bit pressure from a well where the hydraulic model has been used. The pink color are modeled annulus pressure, dotted pink is annulus pressure.

As can be seen there is very huge difference in the simulated and real data value. The simulated value have small deviation from the set point value which is 240 bar.

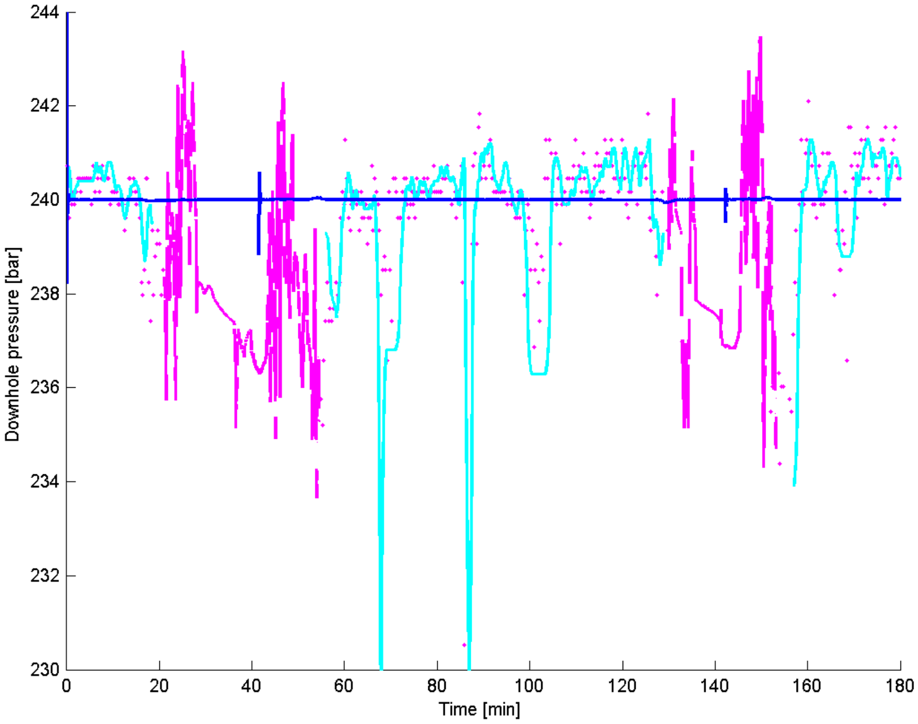

Figure 5.1: Simulated down hole pressure, using nominal plant, compared with real measurement data.

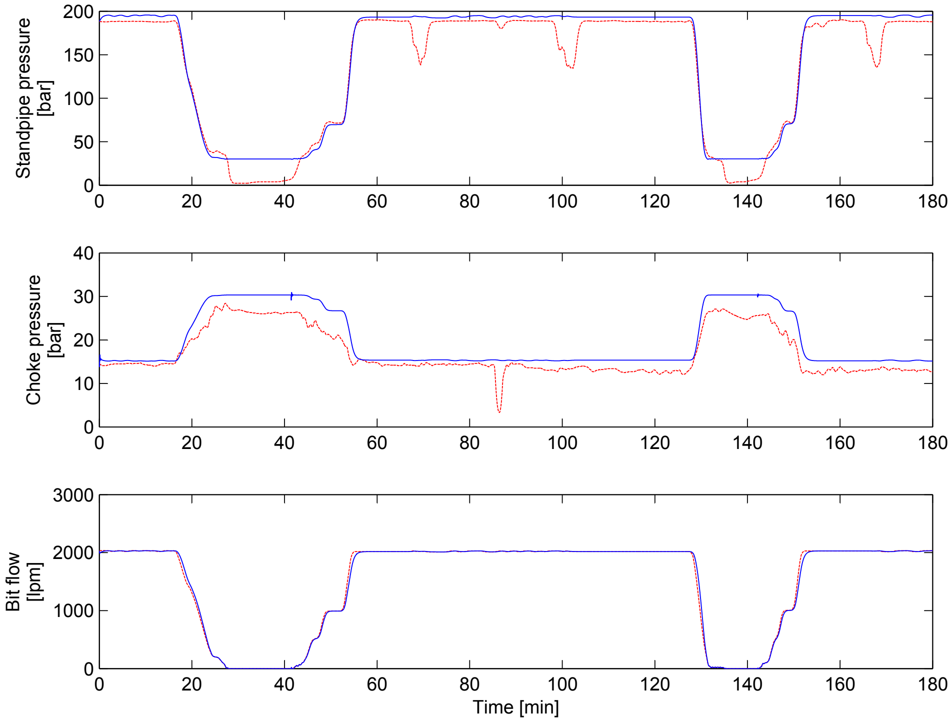

Figure 5.2: Simulated states for nominal plant.

Figure 5.5 show the states p_p, p_c and q_b during simulation.
The figure 5.6 shows plant input and output. The upper plots are the plant output,

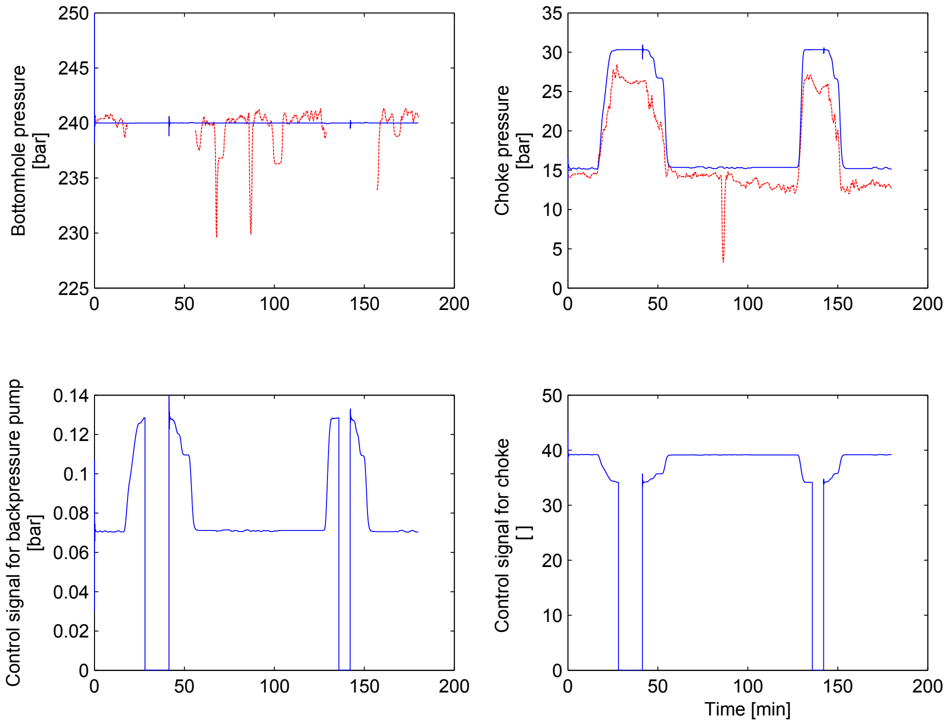

Figure 5.3: Simulated plant input and output for nominal plant

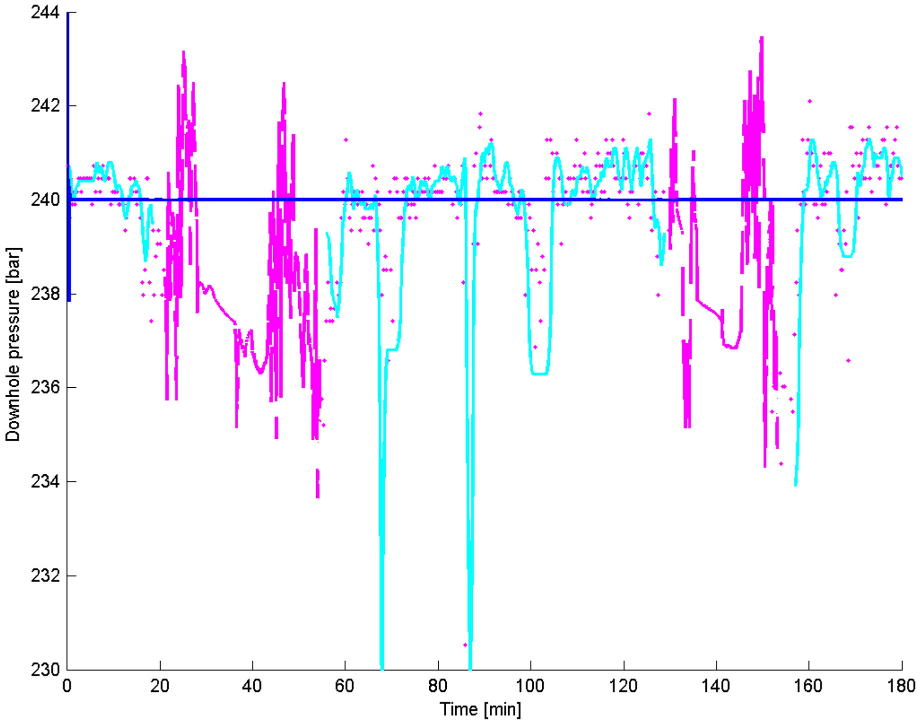

Figure 5.4: Simulated down hole pressure, using fault plant, compared with real measurement data.

p_b to the left and p_c to the right. The lower plots are the plant input q_{bpp} and q_c. Since the choke is blocked the control value of the choke goes to zero. Since the backpressure

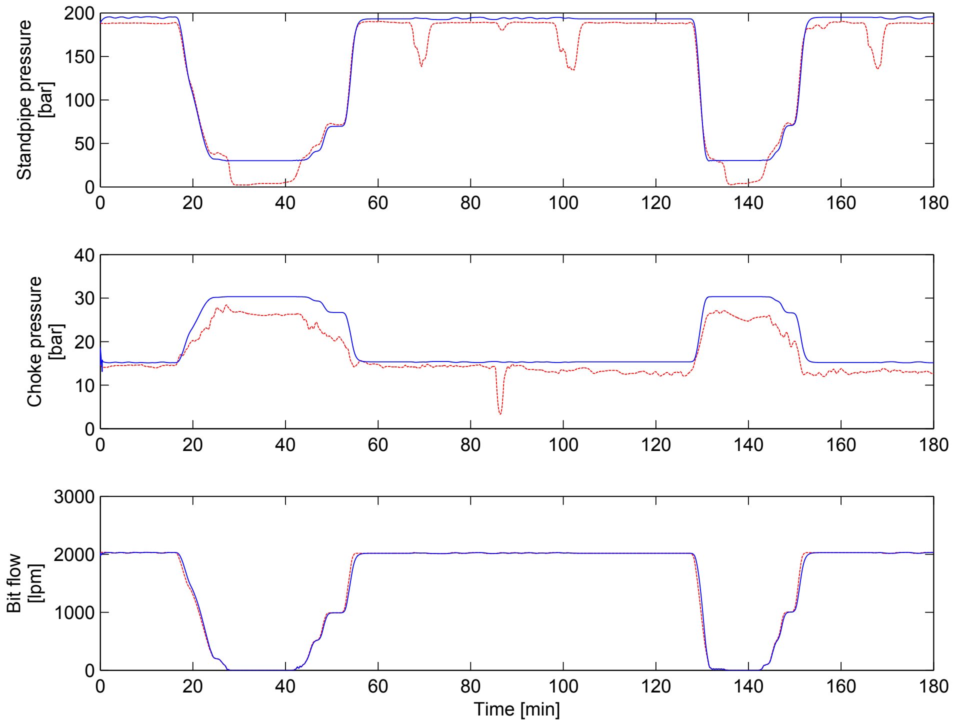

Figure 5.5: Simulated states for faulty plant.

pump q_{bpp} now pumps mud out of the annulus its value are now negative.

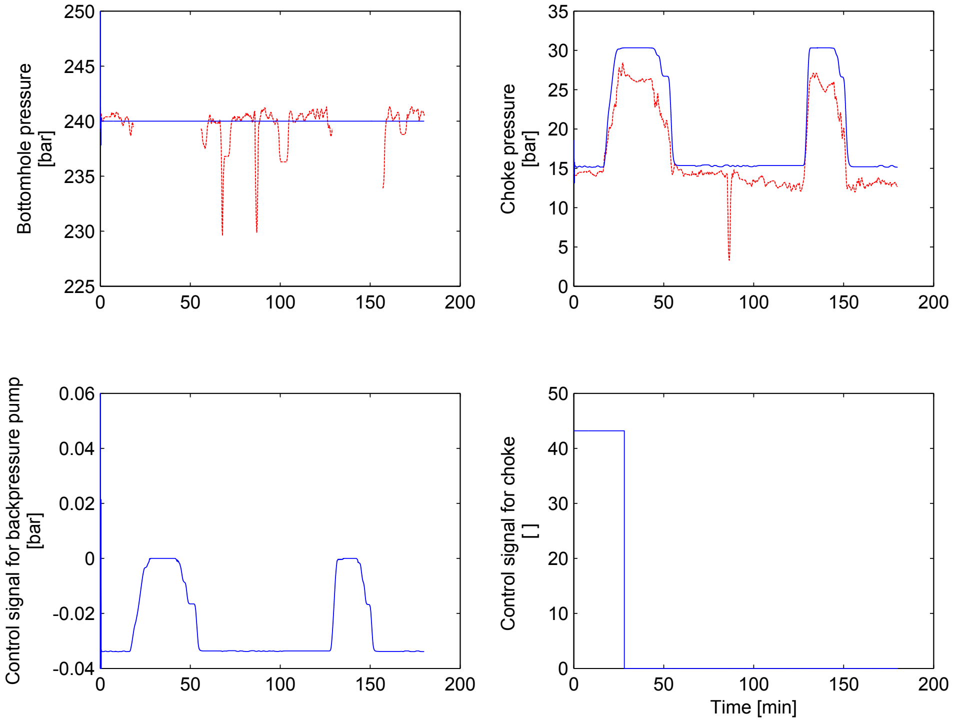

Figure 5.6: Simulated faulty plant input and output

5.3 Simulation with FTC

In this simulation the system are controlled by the nominal controller at the start. After around 25 min there is a fault happening in the system. This happens during shut in and last to somewhere around 60 min into the simulation. At ca. 100 min there are a new fault in the system, this fault last until somewhere around 140 min.

In figure 5.7 there are now more bumps on the simulated BHP p_b. These happen during shut in and transitions between fault and faultless system.

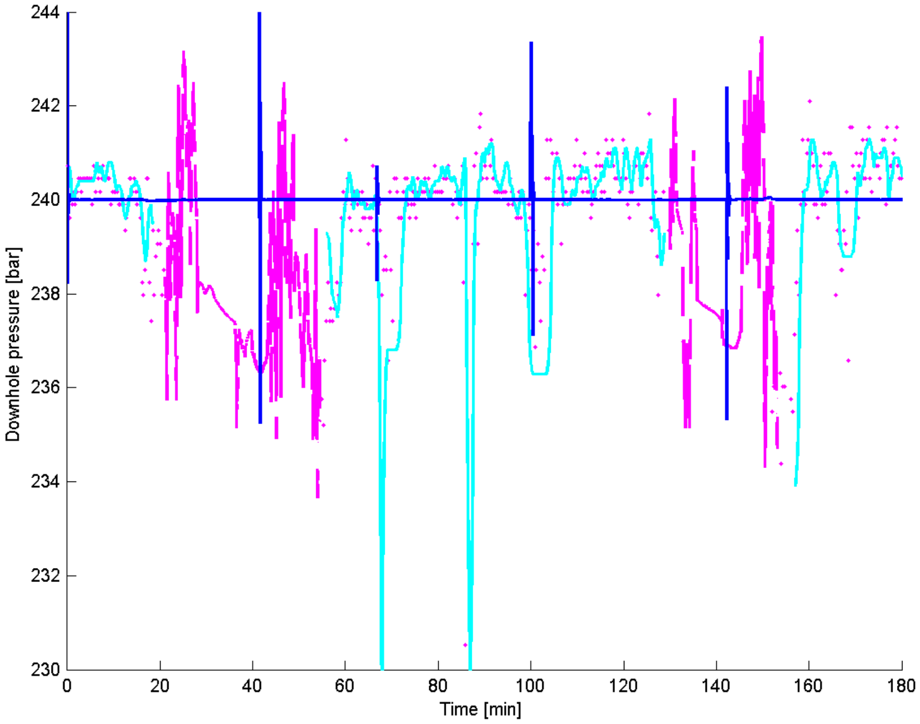

Figure 5.7: Simulated down hole pressure, using FTC, compared with real measurement data.

In figure 5.8 there now are several more bumps in the plot. In the middle plot the choke pressure p_c now have several bumps from transitions between nominal and faultless system. Similar there are some bumps for the flow q at the end of a shut in where the flow increase from zero.

In figure 5.9 the plant output art in the upper part showing the bottom hole pressure and the choke pressure. In the lower part are the back pressure pump to the left and the choke pressure to the right.

The choke pressure is positive while there system acts normal, then during shut in it goes to zero. During the fault from 25-60 min it has a negative flow. Then when returning to normal operation the control value returns to normal, but not to the same amplitude as last time it was in normal operation. Then from 100-140 min it has a new fault where the flow is negative. Then at last the system recovers to normal operation, as can be seen there is a large peak when the system return the normal.

The choke valve operates normal during normal operation but, closes during shut in and remains closed if there is a fault in the system.

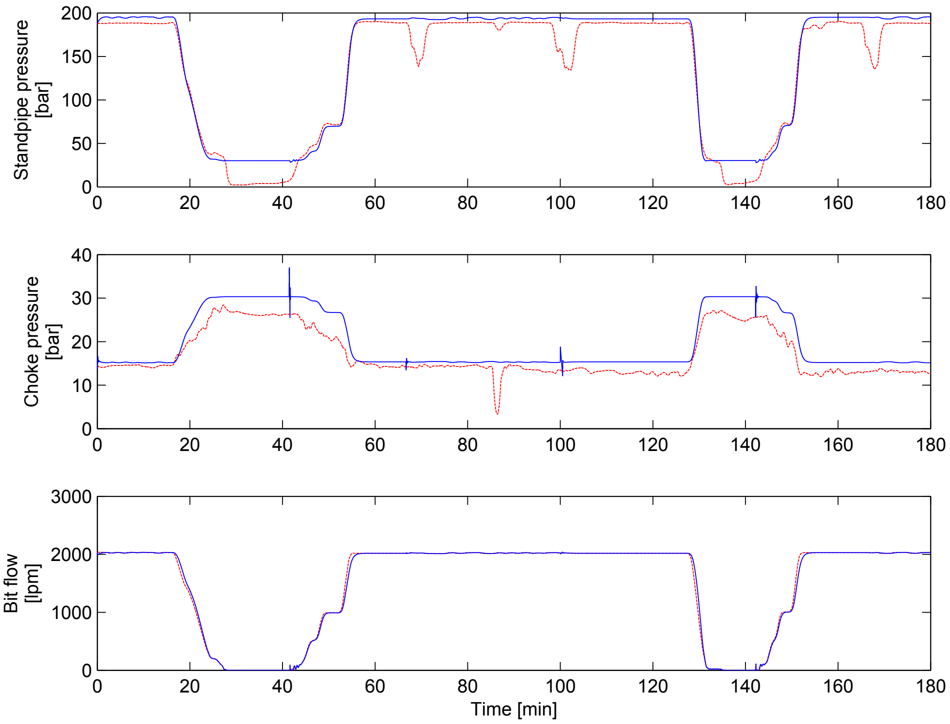

Figure 5.8: Simulated states for FTC plant.

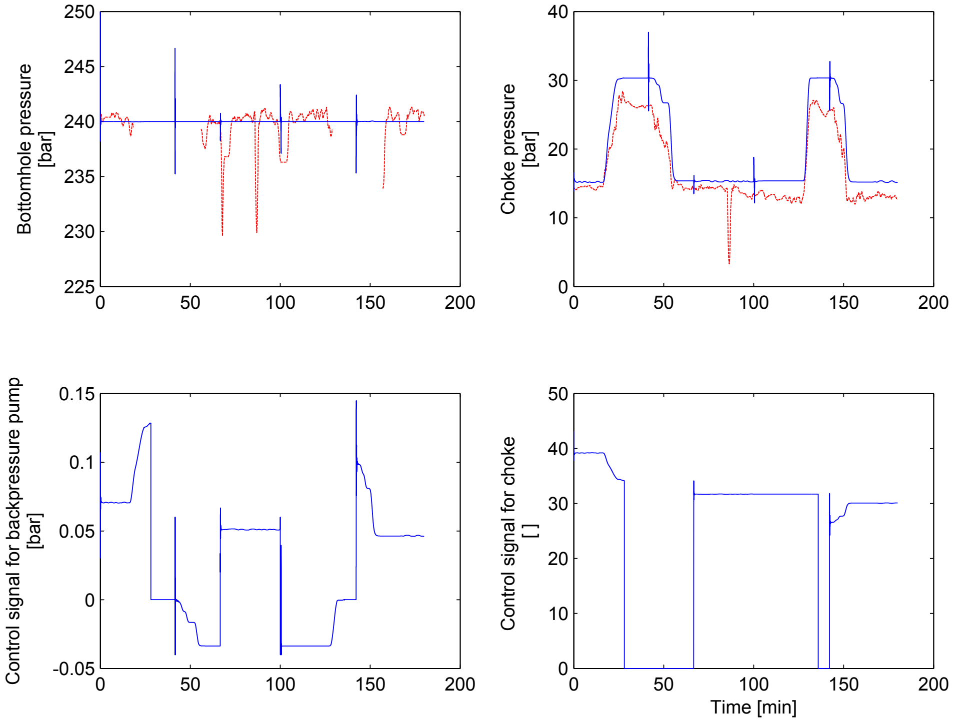

Figure 5.9: Simulated FTC plant input and output

5.4 Simulation with FTC and set point change

This is a similar simulation as in 5.3, but in addition there is a step change in the reference value. After ca. 90 min there are a step change from 240 to 250 bar.

Figure 5.10 shows the system response to a set point change, as can bee seen there is a large overshoot when when the set point is changed.

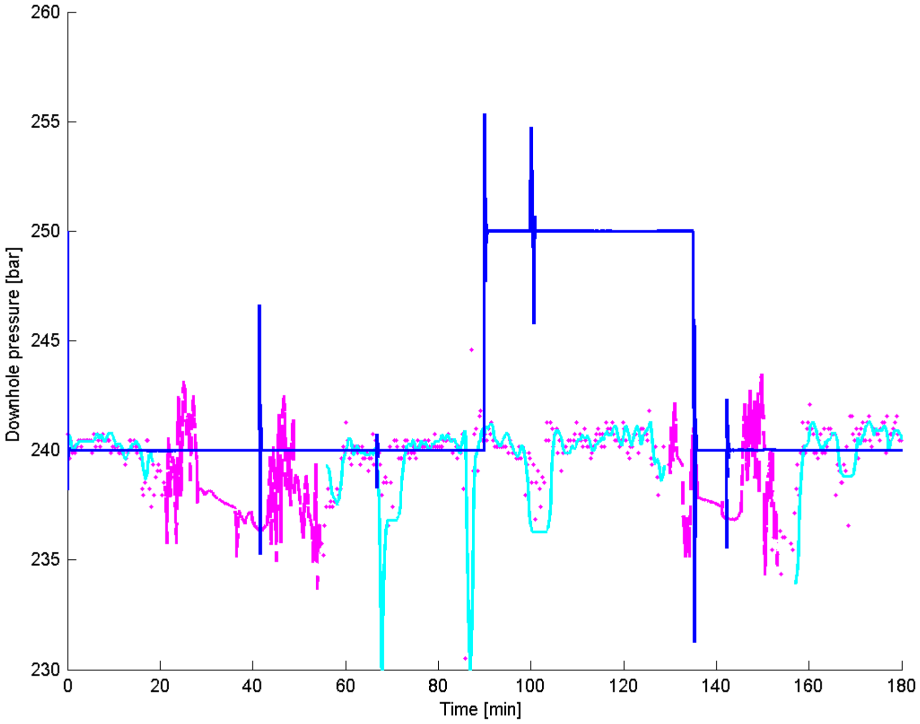

Figure 5.10: Simulated down hole pressure, using FTC and change set point, compared with real measurement data.

In figure 5.11 the set point change is visible at the pump pressure plot and at the choke pressure plot. The set point change is severely more visible in the choke pressure plot than in the standpipe pressure plot. While in the flow plot the set point change is barely visible as small bumps.

If figure 5.12 the input values in the lower part show that the back pressure pump increase the flow during normal operation while the choke close a little.

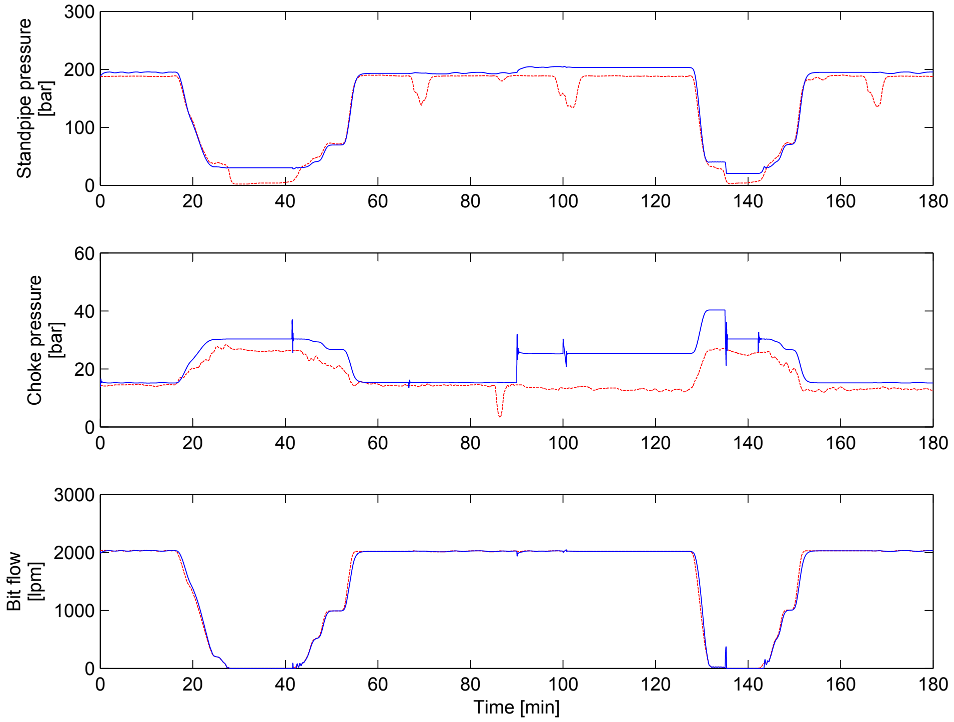

Figure 5.11: Simulated states for FTC plant with set point change.

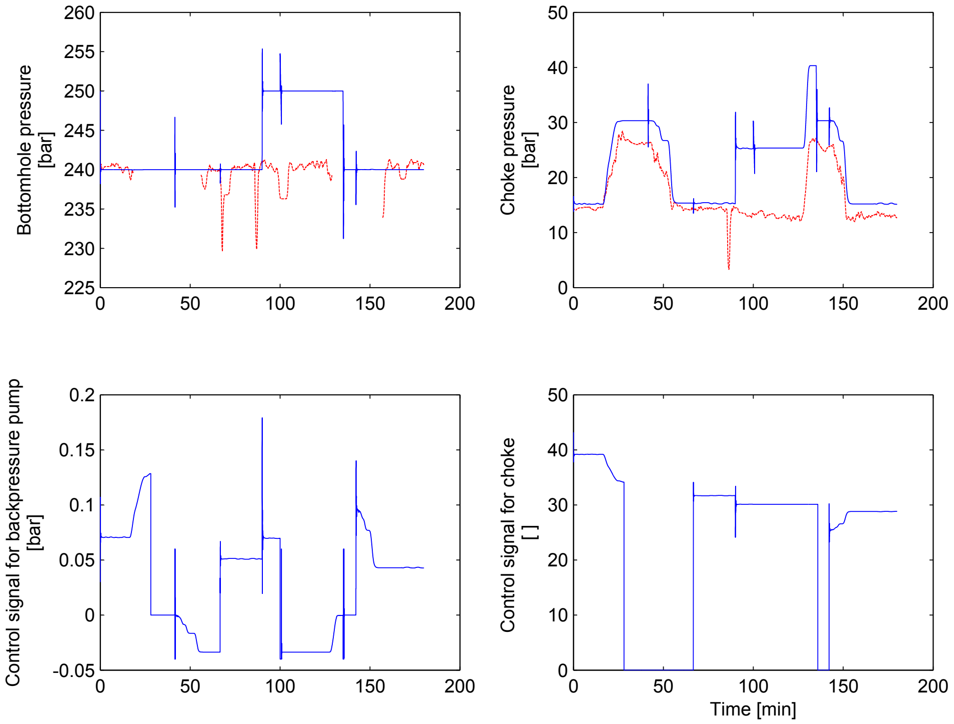

Figure 5.12: Simulated FTC plant input and output during setpoint change

Chapter 6

Discussion

The model used and the simulations have given some interesting results. This part discusses the decisions which have given these results and how some the results could be improved.

6.0.1 Model

The model used in this thesis is a simple one. When a sensor failure or a actuator failure happens it is an easy fault to identify and also to compensate for if there is a suitable redundant candidate to make the system still operative.

When having a blocked choke problem, it does not influence the parameters in the plant model in any way and therefore there is not necessary to have an advanced model, to compensate for the fault.

One problem for the control problem is that most of the faults in drilling are related to the plant itself which means that a state estimator have to be used. The more advanced the model are the more complicated it is make an algorithm to compensate for the fault.

For the model to be used in a more realistic system the system must be augmented with actuator dynamic such that the actuator have more realistic response.

The hydrostatic function $\rho g h$ can be changed such that the pressure are more accurate calculated based on dynamic height and density calculation.

The systems friction calculation can instead of using a simple model based on only the flow q and a parameter F_x use a more advanced fluid mechanic based model.

To compensate for some of the problems mentioned earlier in the thesis it is necessary to extend the model. If drilling is done on a floater heave compensation must be implemented. For heave compensation to be done a model for the drill strings heave motion have to be added to the system.

One other model extension is to implement a model for the reservoir flow q_r. This flow is dependent on the pore and fracture pressure and a model of it could be used to identify well kick.

The drill string length is not the same as drill string depth. The height is used for calculating the hydrostatic pressure. If the mud used is compressible the correct calculation of volume related to height is important.

6.0.2 Faults

The intention for the simulation of FTC is to see if there is possibility's to apply this to a real system. Blocked choke are one fault where there it is easy to diagnose that there is a problem, but it is not that easy to handle the problem. The simulation done here can be used as an indication that there is a possibility that handling blocked choke with analytical redundancy is feasible. There has not been implemented actuator dynamic which would make the system response to dynamic changes severely different. Choke valves usually have very long opening and close time.

The simulations have many problems which is not solved.

Some other problem that is related to MPD is the pack-off and annulus washout. Pack-off happens if the EMD is too low before and during a shut in, this because the reduction in flow reduces the muds ability to transport cuttings. The mud has to be denser to transport the same amount of cuttings when the circulation speed is reduced. Thus it is a problem related to low circulation. One solution is to use MPC to time the density and circulation speed and which can handle the transport delay.

If washout occurs the circulation speed are too fast and the friction between the annulus wall and mud erodes the wall. A solution is to observe if the annulus volume increase faster than a simulation with the same parameters used.

6.0.3 Simulation of normal operation

The results from simulating the system under normal operation manage to hold the BHP p_b at a constant rate but there are some problems with the implementation, the choke closes when the flow stops. In itself this is not a problem other than closing the choke to trap the pressure in annulus will only work for a choke which does not have dynamic implemented. The response if dynamic are implemented is that the choke reacts so slow that the pressure is lost.

A better solution is to freeze the choke position, such that it have a flow orifice function which restricts the flow, during shut in and have the back pressure pump p_{bpp} increase the flow through the choke which then increase the annulus pressure.

The sudden opening of the choke makes the back pressure pump and choke over shoot which results in a bump in BHP p_b.

6.0.4 Simulation of faulty plant

During simulation of the faulty plant the system reacts as intended. The problem is that the choke position should not go to zero it should have been observed such that it has the correct value if the fault is corrected.

6.0.5 Simulation with FTC

When simulating with FTC there is some problems related to the changing from nominal controller to fault controller. The step change during transfer between modes is related to the incorrect initialization of the in-loop controller. Correction of this can be done by applying the not used controllers in separate plant simulation such that the controllers which operate off-line are correct initialized before it is used on-line.

One other problem is that the controllers u_{bpp} and u_c have parameters tuned for a certain amplitudes such that if this distribution is uniform the control response can be sub optimal.

6.0.6 Simulation with FTC and set point change

This simulation has the same problems as for the FTC simulation, what is interesting here is the change in set point. The set point change results in huge overshoot. The overshoot is not significant when it happens during normal operation at 90 min. but at 140 min when there is a fault in the system in addition the change is significant that the overshoot are almost the same as the change in set point.

6.0.7 Simulation with FTC, set point change and reduced sample time

The first bumps are the faults happening and are based on the same sample time as the other simulations.

As can be seen the reduced sample time influence the response from the system when the

Chapter 7

Conclusion

7.1 Conclusion

The simulations done with the hydraulic model shows that FTC is able to handle a fault where the choke valve is blocked. Results from simulations where the choke was blocked during the whole simulation was smooth, but results from simulations with transfer between normal and fault was not bumpless.

Comparison of the simulation results and real data shows significant better control of BHP.

The fault tolerant control is implemented with some simplifications. These simplifications do not interfere with the feasibility that FTC can be used for analytical redundancy such that reduced NPT can be achieved.

There are some problems that are not addressed in this thesis which can have impact on the feasibility, like diagnosis and actuator dynamics.

Implementation of FTC on the hydraulic model is complex and difficult because of the systems dynamic.

7.2 Further work

Further work are divided into three different bulks with different topic. To expand the model it is recommended to look into

- Implement actuator dynamics and constraints.
- Implementation of fault diagnosis.
- Expanding the system to handle other faults
- Dynamic for pore pressure and fracture pressure.

For better understanding of the simulations and control

- Stability proof
- Use of other control method for comparison

Completion of the supervision level system

- Implementation of fault diagnosis.
- Implement observer based anti wind-up
- Implement control reconfiguration for comparison with fault accommodation.

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Appendix A

Appendix

CD with simulation program