CHAPTER ONE

INTRODUCTION

1.1 Overview

Rosaries hydropower plant located on the Blue Nile in Rosaries city, 500km southeast of the capital Khartoum .it consists of 7 unit’s 40MW for each .and the total capacity 280MW. There are two types of water turbines impulse turbines and reaction turbines the type of the hydro turbine use in plant is Kaplan turbine. The basic function of an excitation system is to provide necessary direct current to the field winding of the synchronous generator. The excitation system must be able to automatically adjust the field current to maintain the required terminal voltage. The DC field current is obtained from a separate source called an exciter. The excitation systems have taken many forms over the years of their evolution. The following are the different types of excitation systems [1].The first type is DC excitation systems utilize direct current generators. In such systems direct current is provided to the rotor of the synchronous generator through the slip rings. The exciter maybe placed on the same shaft with power generator or is separately driven by a motor. Exciter may be self–excited or with separate excitation, with permanent magnet generator applied [1].The second type is AC excitation systems utilize AC machines for generator excitation. Exciter is typically placed on the same shaft with the turbine. AC is rectified by controlled or non-controlled rectifiers, to provide DC to the generator field winding. Also AC excitation systems may differ by output control method and source of excitation for the exciter. Presently stationary and rotating AC rectifier systems are in use. In stationary rectifiers the DC output is fed to the field winding of the generator through the slip rings. On the contrary, in rotating rectifiers there is no need in slip rings and brushes and DC is directly fed to the generator field as the armature of the exciter and rectifiers rotate with the generator field. Such systems are known as brushless systems and were developed to avoid the problems with brushes when extremely high field currents of large generators are applied [1]. The third type is Brushless AC excitation systems Brushless systems are used for excitation of larger generators (power over 600 MVA) and in flammable and explosive environments. Brushless system consists of AC exciter, rotating Diode Bridge and auxiliary AC generator realized with permanent magnet excitation. Attempts to build brushless system with Thyristor Bridge were not successful because of problems with thyristor control reliability. The result of this problem is significant disadvantage of these systems, inability of generator deexcitation. Another disadvantage is slower response of system, especially in case of low excitation [1]. The fourth type which is Static excitation system will be discussed in details since it is the type that used in Rosiers Hydropower Plant. In static excitation system, aportion of the AC from each phase of synchronous generator output is fed back to the field windings, as DC excitations, through a system of transformers, and rectifiers. An external source of DC is necessary for initial excitation of the field windings. On engine driven generators, the initial excitation may be obtained from the storage batteries used to start the engine. In our plant this is achieved by afield flashing unit [1].

1.2 Problem statement:

- There is no accurate model for the static excitation system in rosaries hydro power plant for stability studies, and the existing system is single channel type.
- There is no way to estimate the stability bandwidth and to determine the linear model of the excitation system in rosaries hydro power plant.

1.3 Problem solution

- A computerized model for rosaries static excitation system is created depending on the system parameters which are available in the plant documentation.

- A closed loop frequency response is carried out using sine sweep signal (chirp signal) as input to estimate the stability bandwidth and to determine the linear model of the excitation system

1.4 Methodology

- The modeling process based on matlab/Simulink software, which is commonly used in many scientific problems solutions.
- To control the firing angle required to trigger a three phase thyristor converter. Nickolas-Ziegler method is used for tuning the PID gains necessary to reach the desirable stability band.

1.5Thesis outlines

The following provides an outline of this thesis.

In Chapter 2 Rosaries excitation system: focused on a general excitation system and Roseirs Hydro Power Plant excitation system will be discussed in details, since it is the type that used in the power Plant. This chapter illustrates in details the Convertor unit and also the control unit (AVR) which adjusts the firing angle of the converter. And discharge unit which perform tow functions overvoltage protection and field discharge during de excitation. The initial excitation may be obtained from the storage batteries used to start the engine. In this study initial excitation is achieved by afield flashing unit.

Chapter 3 presents the modeling process based on matlab/Simulink software, which is commonly used in many scientific problems solutions.

Chapter4 presents the computer simulations of the existing static excitation system. This chapter illustrates the performance of the model compared to the real system performance.

Chapter 5 concludes the thesis and future work.

CHAPTER TWO

GENERAL EXCITATION SYSTEM

2.1 Functions and Performance Requirements of Excitation Systems:

The functions of an excitation system are:

- to provide direct current to the synchronous generator field winding, and
- to perform control and protective functions essential to the satisfactory operation of the power system

The performance requirements of the excitation system are determined by

- Generator considerations:
- supply and adjust field current as the generator output varies within its continuous capability
- respond to transient disturbances with field forcing consistent with the generator short term capabilities:
    - rotor insulation failure due to high field voltage
    - rotor heating due to high field current
    - stator heating due to high VAR loading
    - heating due to excess flux (volts/Hz)
- Power system considerations:
- Contribute to effective control of system voltage and improvement of system stability [3].

2.2 Elements of an Excitation System:

The elements of excitation system are shown in figure 2.1.

- **Exciter**: provides dc power to the generator field winding
- **Regulator**: processes and amplifies input control signals to a level and form appropriate for control of the exciter

- **Terminal voltage transducer and load compensator**: senses generator terminal voltage, rectifies and filters it to dc quantity and compares with a reference; load comp may be provided if desired to hold voltage at a remote point
- **Power system stabilizer**: provides additional input signal to the regulator to damp power system oscillations
- **Limiters and protective circuits**: ensure that the capability limits of exciter and generator are not exceeded [3].

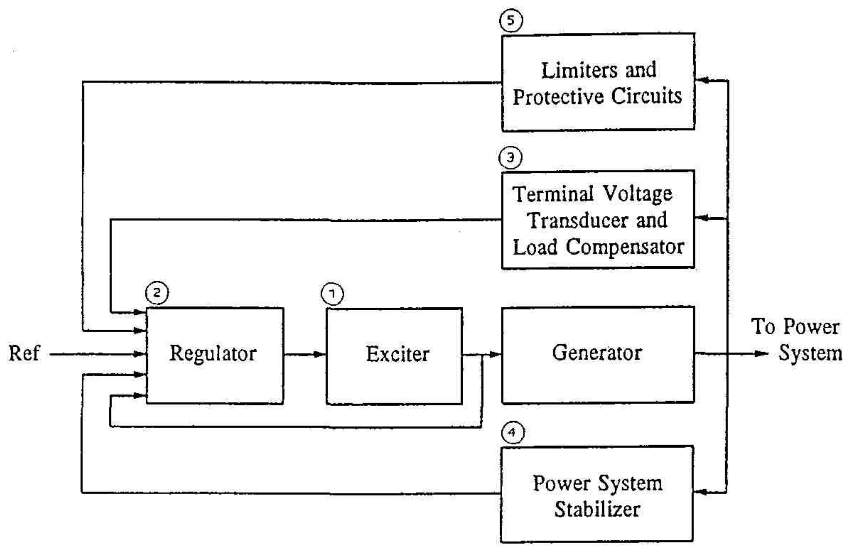


Figure 2.1: Elements of excitation system

2.3 Types of Excitation Systems:

Excitation Systems are classified into three broad categories based on the excitation power source:

- DC excitation systems
- AC excitation systems
- Static excitation systems

2.3.1. DC Excitation Systems:

DC Excitation Systems utilize dc generators as source of power; driven by a motor or the shaft of main generator andself or separately excited. They represent early systems (1920s to 1960s) and lost favor in the mid-1960s because of large size; superseded by ac exciters.

The voltage regulators range from the early non-continuous rheostatic type to the later system using magnetic rotating amplifiers.

Figure 2.2 shows a simplified schematic of a typical dc excitation system with an amplidyne voltage regulator

- Self-excited dc exciter supplies current to the main generator field through slip rings
- Exciter field controlled by an amplidyne which provides incremental changes to the field in a buck-boost scheme
- The exciter output provides rest of its own field by self-excitation [3].

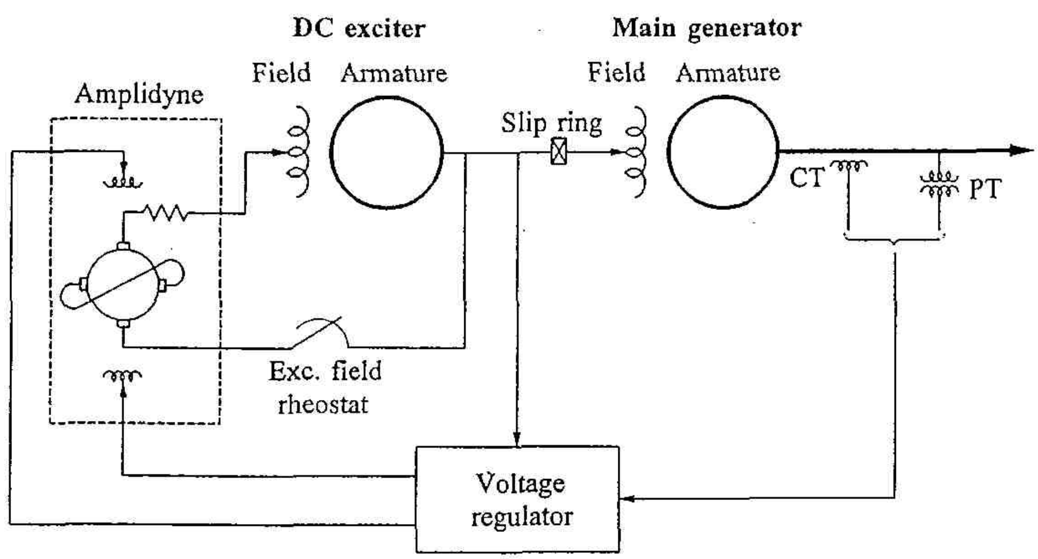


Figure 2.2: DC excitation system with amplidyne voltage regulators

2.3.2. AC Excitation Systems:

The AC Excitation Systems use ac machines (alternators) as source of power. Usually, the exciter is on the same shaft as the turbine-generator. The ac output of exciter is rectified by either controlled or non-controlled rectifiers. The rectifiers may be stationary or rotating.

The early systems used a combination of magnetic and rotating amplifiers as regulators; most new systems use electronic amplifier regulators [3].

2.3.3. Static Excitation Systems:

All components in the Static Excitation Systems are static or stationary. The dc is supplied directly to the field of the main generator through slip rings. The power supply to the rectifiers is from the main generator or the station auxiliary bus [3].

2.3.3.1. Potential-source controlled rectifier system:

The excitation power in this type is supplied through a transformer from the main generator terminals and regulated by a controlled rectifier as shown in figure 2.3. It is commonly known as bus-fed or transformer-fed static excitation system and it has very small inherent time constant. The maximum exciter output voltage is dependent on input ac voltage; during system faults the available ceiling voltage is reduced [3].

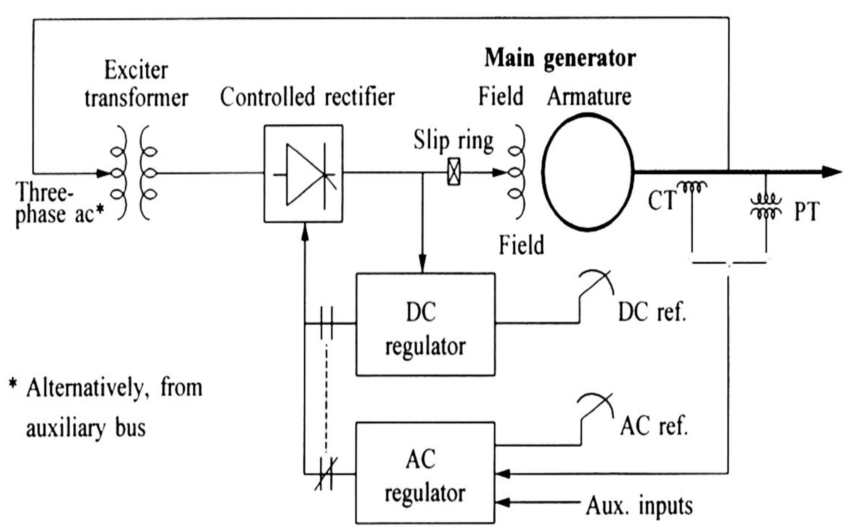


Figure 2.3: Potential-source controlled-rectifier excitation system

2.3.3.2. Compound-source rectifier system:

The power to the exciter in this type is formed by utilizing current as well as voltage of the main generator and this is achieved through a power potential transformer (PPT) and a saturable current transformer (SCT). The regulator controls the exciter output through controlled saturation of excitation transformer (see figure 2.4). During a system fault, with depressed generator voltage, the current input enables the exciter to provide high field forcing capability [3].

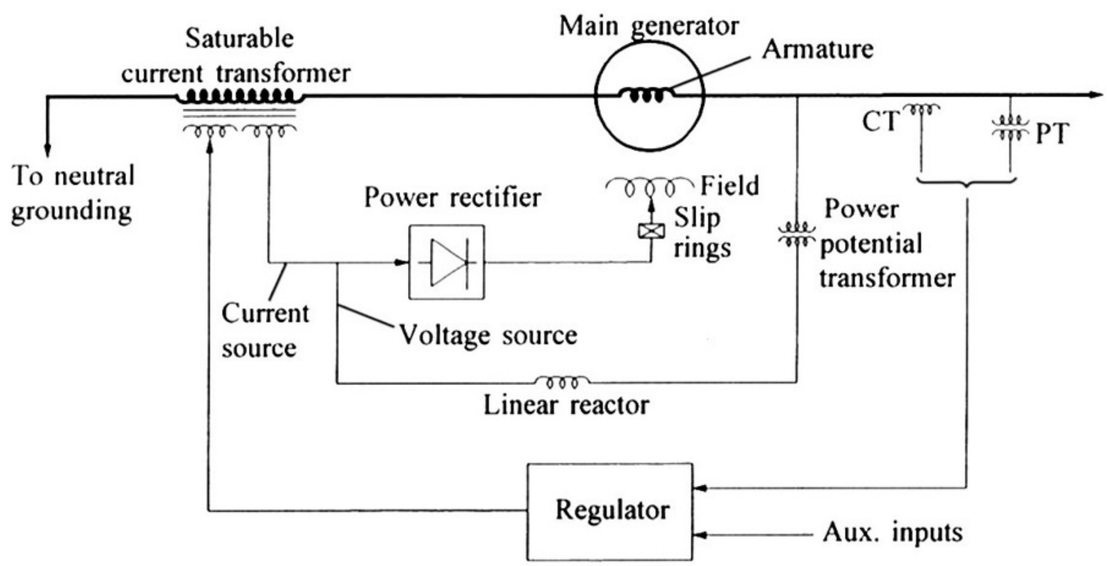


Figure 2.4: Compound-source rectifier excitation system

2.3.3.3. Compound-controlled rectifier system:

This type of static excitation system utilizes controlled rectifiers in the exciter output circuits and the compounding of voltage and current within the generator stator as in figure 2.5. The result is a high initial response static system with full "fault-on" forcing capability [3].

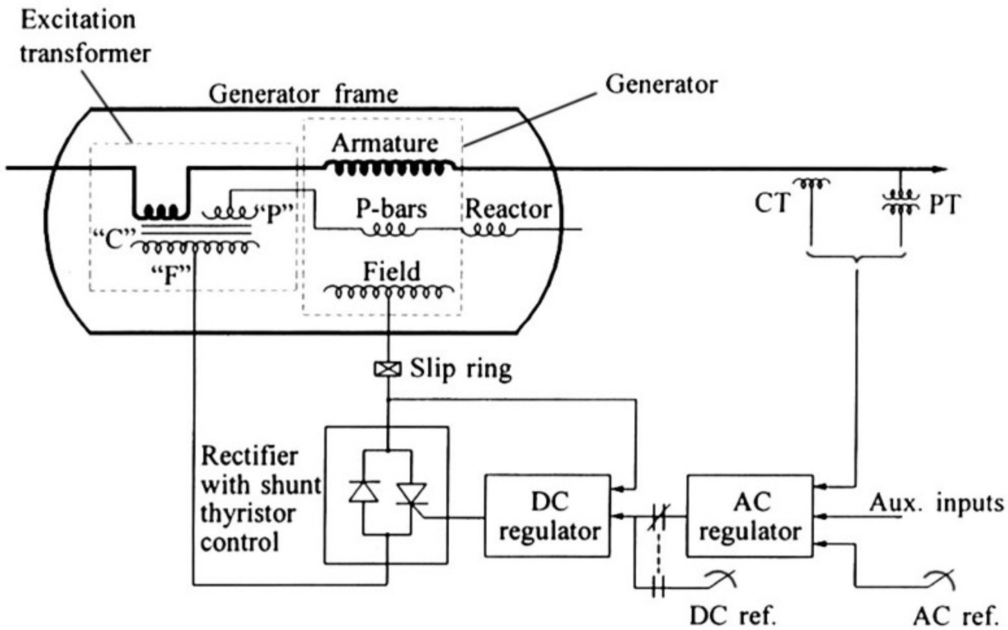


Figure 2.5: Compound-controlled rectifier excitation system

2.4. Overall System Description

A static excitation system regulates the terminal voltage and the reactive power flow of the synchronous machine by direct control of the field current using thyristor converters. According to the block diagram of an UNITROL 5000 Excitation System for approximately3200 A, which is shown on figure 2.6. Block diagram of a typical UNITROL 5000 Excitation System, the entire system can be divided into four major function groups:

· Excitation transformer -T02

· Excitation modules with control electronics (-A10, -A20)

· Thyristors converter units -G31 to -G34

· Field flashing (-R03, -V03, -Q03) and field suppression equipment (-Q02, -F02,-R02) [4].

In static excitation systems (so-called shunt excitation or self-excitation), the excitation power is taken from the machines terminals. The field current of the synchronous machine flows through the excitation transformer -T02, the field circuit-breaker -Q02 and the power converter G31 to G34 (thyristor converter). The excitation transformer reduces the generator terminal voltage to the required input voltage for the thyristor converter, provides the galvanic isolation between the machine terminals and the field winding and acts at the same time as the commutating reactance for the thyristor converter. The power converter G31 to G34 converts the AC current into a controlled DC current If. At the beginning of the starting sequence the field flashing energy is derived from the residual machine terminal voltage. As soon as 10 to 20 V at the input of the thyristor converter are reached, the thyristor converter and control electronics are ready for the normal operation and a soft-start sequence takes place. The new start up facilities and design of the field flashing equipment (-R03, -V03, -Q03), which have been developed for UNITROL 5000, are more described in chapter 7 of this document. After synchronizing with the network the excitation system can operate in AVR mode regulating the generator terminal voltage and reactive power or can operate in one of the superimposed mode. That is, machine's Cos-phi control or MVAr (reactive power) control. In addition, it can be included in an overall joint voltage and reactive control of the power plant [4].

The purpose of the field suppression equipment is to disconnect the excitation system from the excitation transformer and to discharge the field winding energy as fast as possible. The field suppression circuit consists basically of the field circuit breaker -Q02,the field suppression resistor -R02 and the CROWBAR thyristors -F02 with their associated triggering electronics. The field suppression with field circuit breaker on the AC side of the thyristor converter is described in greater detail in chapter 6 of this document. If explicitly requested in the technical specifications and based on the ratings of the excitation system, the field circuit breaker may be connected at the DC side of the thyristor converter. This solution mainly takes place for the field currents of more than 3500 A [4].

Based on the system requirements the control electronics is configured as a single AVR channel (-A10) or double AVR-channel (-A20). One channel comprises basically one Excitation Module with a Control Board (COB) and a Measuring Unit Board (MUB), forming an individual processing system. Each channel contains the Software for the machine terminal voltage regulation, field current regulation, excitation monitoring / protection functions and a programmable logic control. In a single AVR-channel configuration a separate controller so called Extended Gate Controller (EGC) is employed as a back-up channel that is a MANUAL controller [4].

In addition to control electronics interface cards such as Fast Input / Output (FIO) and Power Signal Interface (PSI) are employed to provide the galvanic separation of the measuring and control signals. Further, each thyristor bridge is equipped with a set of the converter interface cards including Converter Interface (CIN), Gate Driver Interface (GDI) and Converter Display (CDP). UNITROL 5000 has a facility, by extension, for connection to a serial communication link. For example a Modbus type serial interface can be applied. In addition, TCPIP type serial interface with Ethernet protocol can be provided optionally. Within the excitation system the exchange of the control and status signals is performed serially over the ARC net Field bus. The field-breaker tripping circuits are additionally hard-wired [4].

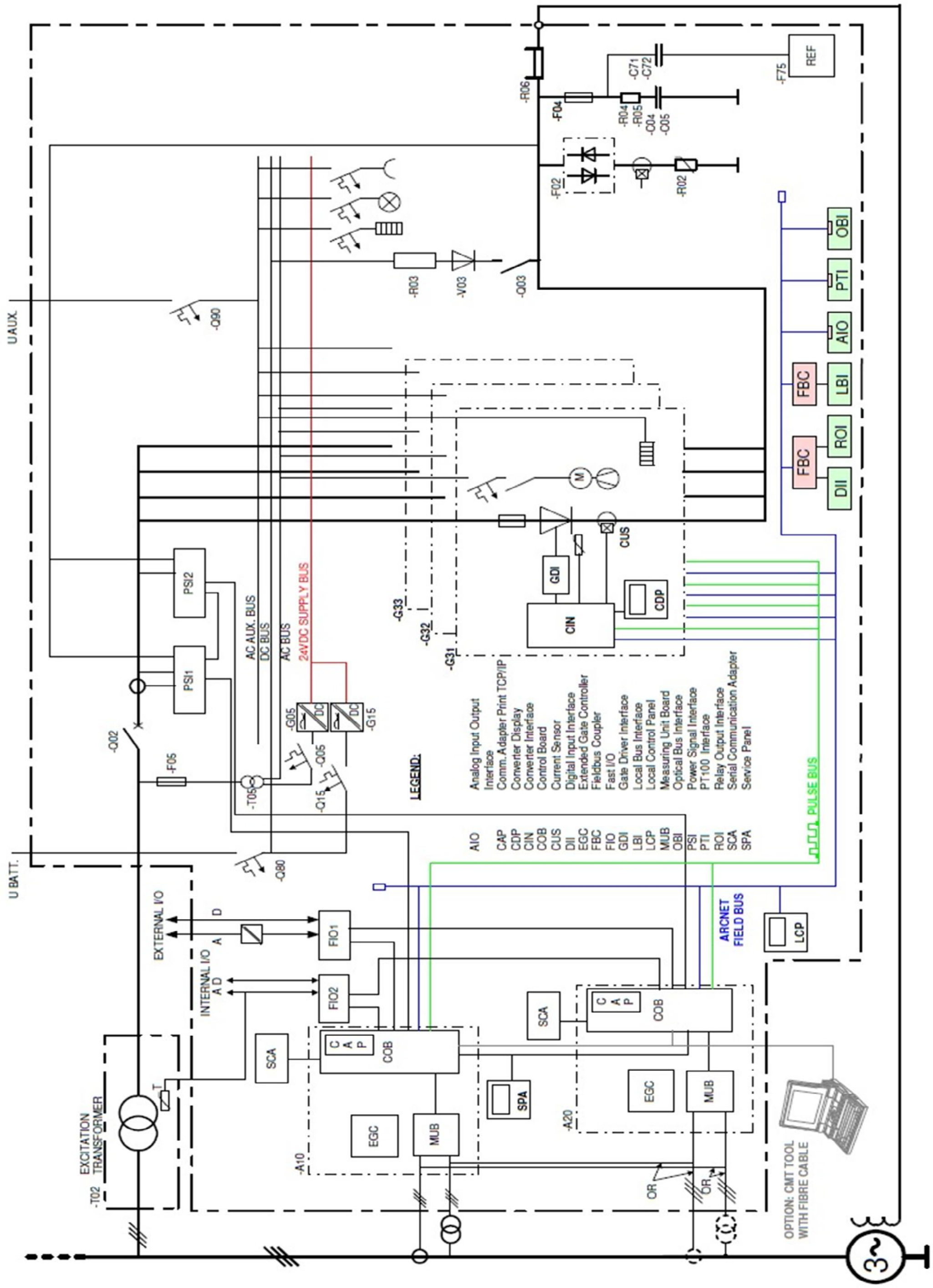


Figure 2.6: Block diagram of a typical UNITROL 5000 Excitation System.

2.4.1. UNITROL 5000 Control Electronics

UNITROL 5000 is the microprocessor based control system. The platform for the control electronics is an enhanced version of DCS 500 System mainly intended for the control and regulation of the large static drive systems. By development of the control electronics several elegant solutions and facilities for of the excitation systems were introduced, for example dynamic current distribution mechanism for parallel operation of thyristor bridges and start up from the residual machine terminal voltage. Further, the communication and diagnostic features were also improved. In its special versions UNITROL 5000 has facilities to be supplied from the network frequency of 16 2/3 Hz or from the high frequencies exciter machines up to 500 Hz [4].

2.4.1.1. Configuration and Mechanical Design

The core of the control electronics is a Control Board (COB) for all the regulation and control functions as well as for the pulse generation. In addition, a Measuring Unit Board(MUB) with a digital signal processor is applied for the fast processing of the actual measuring values. These boards are attached together in a way to reassemble a double layer board and are assembled in a metallic case, making up an individual processing channel. In such a configuration an Extended Gate Controller (EGC), which is mechanically separated, is used as a back-up channel for the field current regulation. In a fully redundant system a second double layer board assembled in a separate metallic case is provided (second channel). That is, both channels are mechanically separated, enabling an easy maintenance on-line. Each channel of the control electronics can control one or more parallel connected thyristor converters with the system rated current up to10’000 A [4].

The interface devices such as Fast I/O card and Converter Interface (CIN) are applied for the galvanic separation and matching of the control signals and are placed where the signals are originated, e.g. one converter interface is placed into each thyristor unit. The communication within the excitation system, if not time critical, is performed serially over the ARC net Field Bus [4].Possible configurations with UNITROL 5000 System are shown on the Figure 1 to Figure9. The abbreviations to the figures are as follows:

AVR - Automatic Voltage Regulator

FCR - Field Current Regulator

BFCR - Backup Field Regulator

UG - Measuring signal of the generator terminal voltage

IG - Measuring signal of the generator terminal current

IF - Measuring signal of the generator field current

The two controller states are “on-line” and “stand-by”. The latter is a backup for the “online “controller.

Figure 2.7 shows a minimum configuration of UNITROL 5000 System which is used in Roseirs Hydro Power Plant. The main Control Board (COB) provides all regulation and control functions including a field current regulator. The Backup Regulator, which function is included in the Extended Gate Controller (EGC), follows the main control and takes over automatically in case of failure of the main control. One thyristor bridge without redundancy is employed in this configuration [4].

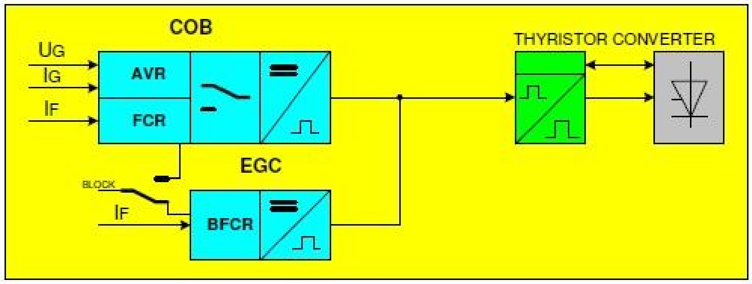


Figure 2.7: Type D5E – Single Channel and Back up Control with a Single Converter.

Figure 2.8 shows another configuration, called Twin Configuration where two fully redundant converters are employed. Any of these can be chosen as the "on-line" converter, whereas the other is in "stand by". This configuration is usually applied for the rated currents up to 1800 A [4].

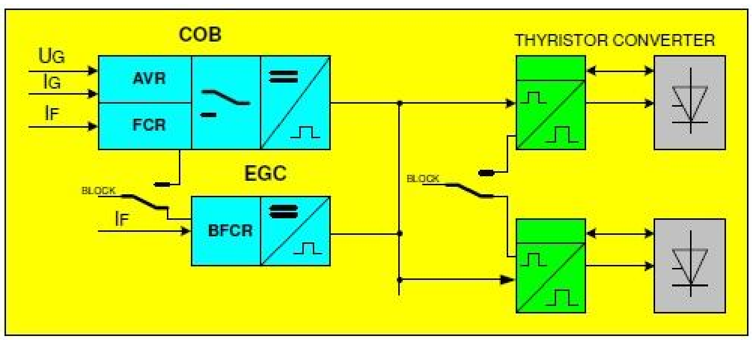


Figure 2.8: Type D5T – Single Channel and Back up Control with fully Redundant Twin Converters.

In the followings configurations, Figure 2.9 to Figure 2.11, a full redundant dual channel control is employed. Each of the control channels can be "on line" or in a "stand by" mode. In addition to the automatic voltage regulation each channel also includes software functions for PSS, limiters, protections and monitoring as well as the Manual Control [4].

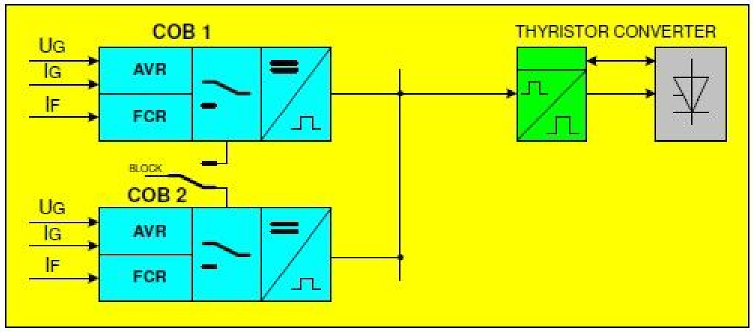


Figure 2.9: Type A5E – Full redundant dual channel control with Single Converter.

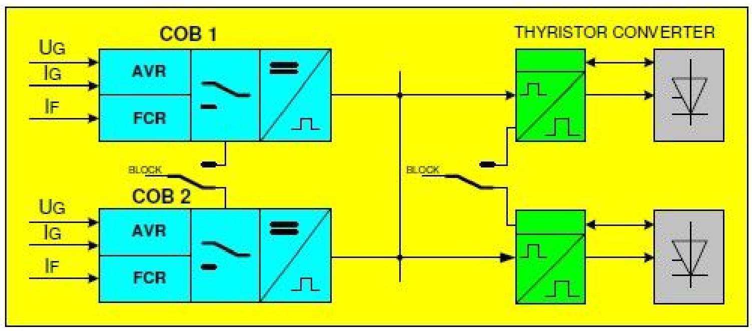


Figure 2.10: Type A5T – Full redundant dual channel control with Twin Converters.

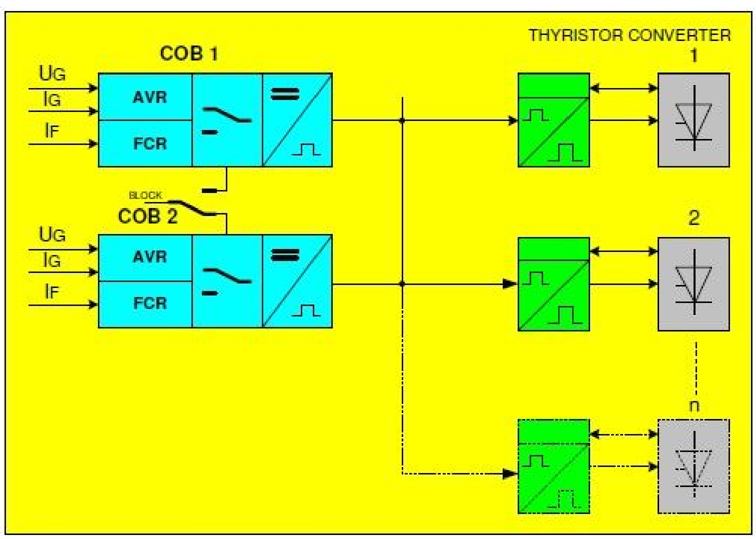


Figure 2.11: Type A5S – Full Redundant Dual Channel Control with Redundant n-1 Converters.

2.4.1.2. Main Control Boards

Implementation of the automatic voltage regulation, limiters, protection and control functions into a single processing board was possible due to its high performance and computing power of the Control Board (COB). It basically contains an enhanced microprocessor, which operates with 32 MHz clock. An ASIC (Application Specific Integrated Circuit) takes care of exchange and storage the data, control pulse generation, A/D and D/A conversion and interfacing with other devices within excitation system(ARC net Field bus coupler). It supports the communication with the local control, service panels and CMT-Tools. Further, it provides serial ports and has a self-diagnostic function (watchdog). For the rapid diagnostics and fault tracing purposes Control Board is equipped with a seven-segment alarm display [4].

A typical configuration of the double channel system is shown on Figure 2.12.

Further, for the diagnostics purposes the control board is equipped with a transient recorder and fault logger. These are handled with the CMT-Tools (Commissioning and maintenance tools). The fault logger and transient recorder can also be synchronized with the real time clock [4].

By the extensions with sub-prints or adapters the serial communication links to the Digital Control System can be provided. The particular functions and merits of the system are described in separate items of this document [4].

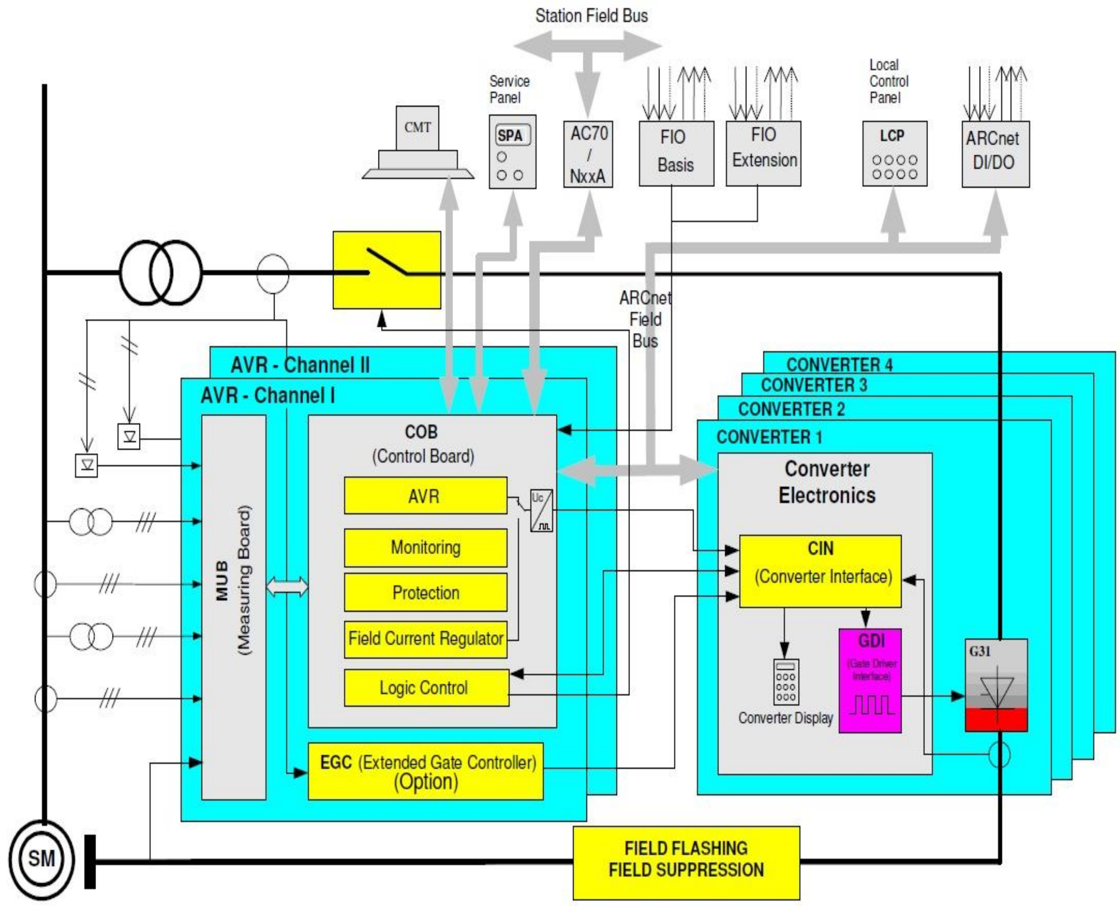


Figure 2.12: Typical configuration of the double channel system.

2.4.1.3. Measuring Unit Board (MUB)

Measuring Unit Board (MUB) consists of a Digital Signal Processor (DSP). This provides fast processing of the actual measuring values, galvanic separation and level matching.

The following functions are implemented in the Measuring Unit Board (MUB):

- Filtering and digitizing.

- Calculation of synchronous machine's voltages and currents from the PT's and CT's signals as well as the calculation of the active and reactive power; Cos-phi and machine's frequency.

- Power System Stabilizer (PSS) with accelerating power and frequency input signals, in which the control algorithm is based on IEEE Std. 421-Type 2A.

- Adaptable Power System Stabilizer (an alternative to the PSS) [4].

2.4.1.4. Extended Gate Controller (EGC)

Extended Gate Controller (EGC) is employed as a back-up controller in single automatic channel configurations and for the pulse generation of the system rated frequencies different from 50/60 Hz. In latter case, its typical application is for the automatic voltage regulators supplied from the high frequency pilot exciters, whose rated frequency can be up to 500 Hz. Further, it is applied in excitation systems for the generators of 16 2/3 rated frequency for railway networks. This controller is assembled in the same case as the above-mentioned boards but is mechanically separated. The following functions are also implemented in this board:

- Field current regulation.
- Follow up control for the smooth change over in case the control board (COB) fails.
- Back-up over current relay, instantaneous (ANSI 50).
- Back-up over current relay, inverse-time (ANSI 51).
- DC short circuit protection.
- Thyristor converter conduction monitoring based on the ripple monitoring principle.
- Inherent power supply [4].

2.4.1.5. Power Signal Interface (PSI)

Power Signal Interface (PSI) is used for the galvanic separation and matching of the field measurement signals, before being sent to the Measuring Unit Board (MUB) [4].

2.4.1.6. Power Supply of the Control Electronics

All electronic devices are supplied from a 24 VDC bus. The 24 VDC bus is derived from two fully redundant power packs; a DC/DC-power pack which is supplied from a DC source (e.g. station battery) and an AC/DC-power pack which is usually supplied from the secondary side of the excitation transformer [4].

2.4.1.7. Communication within the Excitation System

The communication within the excitation system is performed serially via the so-called ARC net field bus. For example, this internal communication link is employed for the exchange of the control and status signals to/from the thyristor converter. Further, the measured values and the alarms for the Local Control Panel (LCP) as well as the local control commands are sent through this link [4].

2.4.1.8. Human-Machine Interface

A user-friendly Local Control Panel (LCP) can be used for the local control and supervision of the excitation system. It can be located in the Power Station Control Room, serving for the remote control (see figure 2.13).

The panel offers following facilities:

- Display of measuring and processing signals on 8 display lines, each containing 40 characters (240 x 64).

Either 8 analogue signals or 4 with analogue – bar display in scale from 0 to 120% can be displayed simultaneously. A maximum of 32 pre-defined signals can be selected. Display mode is enabled with the function keys. Signal selection is performed by means of the scroll key or page keys. A display line is chosen with the cursor key [4].

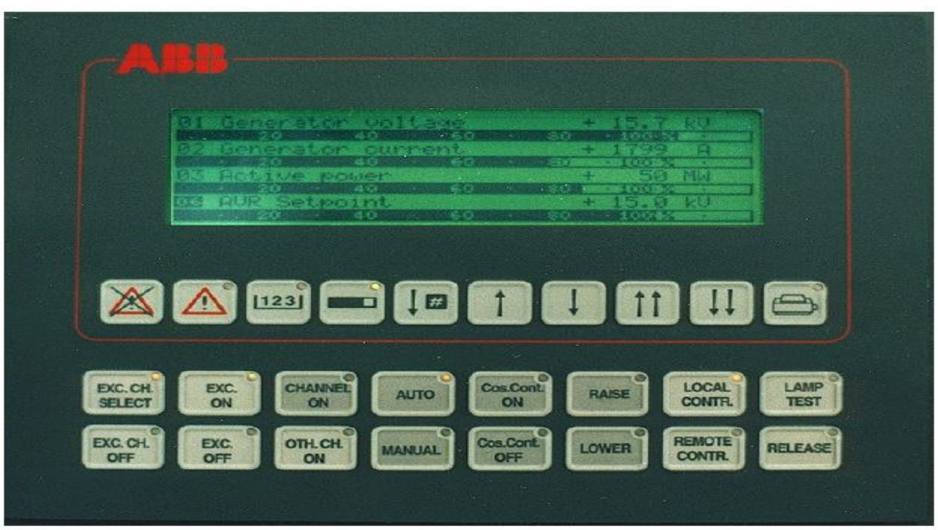


Figure 2.13: Local Control Panel (LCP) in a typical operation.

- Alarm annunciation

In case of their appearance the excitation system alarms take precedence over the measuring signal display.

The displayed alarm includes its alarm number and description text of 40 characters. 8alarm messages can be displayed simultaneously. The first occurred alarm appears on the first line and following alarms appear in order of their alarm numbers. If more than 8alarms appear, they can be displayed by the scroll key. Maximum 80 alarms can be displayed. On the alarm function key there is an alarm LED, that blinks by each alarm occurring.

After pressing the confirmation key the alarm LED changes to a steady light as long as an alarm exists. When the alarm disappears, the alarm LED switches off.

- Printing of the signals and alarm messages

The information saved by the control panel can be printed out over its serial interface portRS-232.

- Indication of the selected mode

Each of selected mode keys is equipped with a LED for mode indication.

- Local operation control

16 function keys with LED’s for status indication are available for local operation control of the excitation system [4].

2.4.1.9. Control Interface to the Power Station Control System

The digital and analogue command and status signals are interfaced via the Fast Input /Output boards (FIO). Each fast Input / Output board (FIO) is equipped with:

- 16 Digital inputs with opto-couplers, rated for 24 VDC. The control inputs are activated using a local 24 VDC from the internal power packs

- 18 output relays with change over contacts for status indications and alarms

- 4 multipurpose analogue inputs + 10 V or + 20 mA
- 4 multipurpose analogue outputs 4 to 20 mA
- 3 analogue inputs for excitation transformer temperature measuring PTC or PT100.

A maximum number of two Fast Input / Output boards can be implemented per system, which is sufficient for most system requirements. In case that more digital inputs and outputs are requested, the system can be supplemented with Digital Input Interface (DII)and Relay Output Interface (ROI). These are connected to the ARC net Field Bus over a Field Bus Coupler (FBC).

Standard interface signals are assigned according to Table 1.

Two separate hard-wired signals of the internal trip are available for the generator protection system. Two trip signals from the generator protection are foreseen to act directly on the excitation trip circuits [4].

Table 2.1: List of standard remote control, status and alarm signals.

Order Commands		Status and Alarm Signals	
- Excitation	Start	- Excitation	On
- Excitation	Stop		
- Field Breaker	On	- Field Breaker	On
- Field Breaker	Off	- Field Breaker	Off
- Generator Breaker	On Line		
- AUTO	On	- AUTO	On
- MANUAL	On	- MANUAL	On
- Imposed Control (Cos-phi or VAR Control)	On	- Imposed Control (Cos-phi or VAR Control)	On
- Imposed Control (Cos-phi or VAR Control)	Off		
- Setpoint	Raise	- Setpoint	Max
- Setpoint	Lower	- Setpoint	Min
		- Local operation	On
		- Over excitation limiter	Active
		- Under excitation limiter	Active
		- Ready for change	AUTO/ MAN
		- Back up Controller (BFCR), if applicable	On
		- Common Alarm	On
- Machine Speed	> 80%		

2.4.2. Voltage Regulation, Monitoring and Protection Functions

An overview of the main control functions implemented into the UNITROL 5000 is provided in the following items.

2.4.2.1. Functions covered by the Control Electronics

The main objective of an automatic voltage regulator (AVR) is the accurate control and regulation of the terminal voltage and the reactive power of a synchronous machine. In order to fulfill this requirement, the field voltage must react quickly to changes of the operating conditions, i.e. with a response time that does not exceed a few milliseconds.

To accomplish this, a high-speed controller is required. It shall compare continuously the actual values with the set-point values and vary the final control element (firing angle for the thyristor converter) with an insignificant delay.

The UNITROL 5000 digital voltage regulator calculates the controlled variable from the measured and the set-point value in very short time intervals. The result is a quasi continuous behavior with a negligible time delay (comparable with an analogue regulator).

The calculations are fully digital. Analogue measurement signals such as terminal voltage and current are converted into digital signals by analogue/digital converters, which are parts of the Measuring Unit Board (MUB). The set points and limit values are already defined in digital form.

Figure 2.14 shows the overall software's functions of an AVR, which are implemented into standard UNITROL 5000 static excitation system. For a better understanding of those software's functions, they are split into functional blocks followed by the short functional description. The numbers (X) within the functional blocks correspond to those mentioned in the descriptions [4].

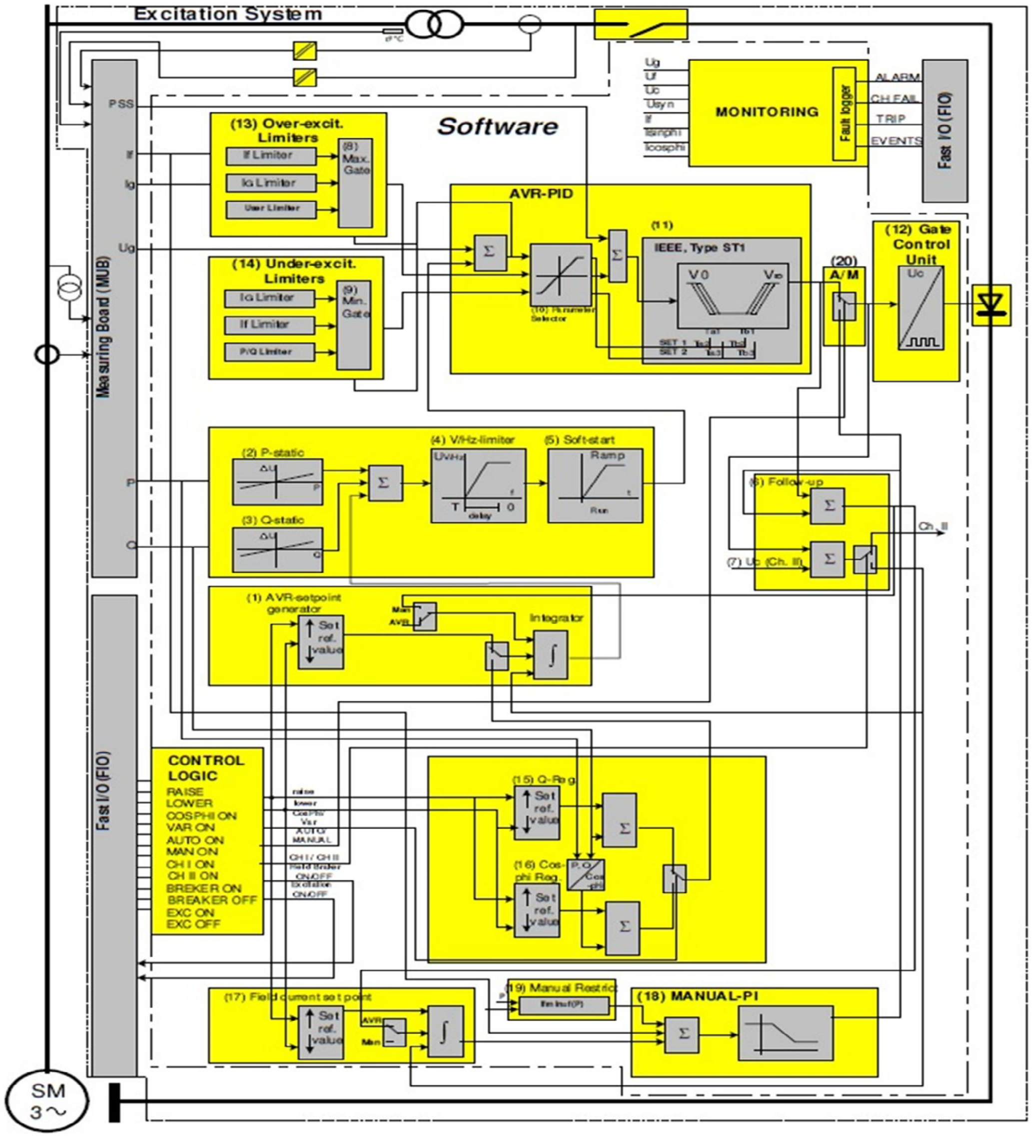


Figure 2.14: Internal structure of UNITROL 5000 Automatic Voltage Regulator.

2.4.2.2. Set point Generation and Voltage Regulation

(1) AVR set point generator can be raised, lowered or reset to a pre-set value using digital input commands or analog input signals or through the serial communication link. The excursion time from minimum to maximum limits can be adjusted independently from the set point range [4].

- **Active and reactive power compensation**

(2) P-static and (3) Q-static, are intended to add additional signals proportionally to the active or the reactive power to the set-point value. The reason is the compensation of the voltage drop caused by the active or reactive power across the unit transformer and/or the transmission line. The reactive power signal is also necessary for parallel operation of two and more generators connected to the same bus. In this case, the Q-Static signal shall reduce the AVR set point proportionally to the increase of reactive power. The rate of change of the set point as function of the active and/or reactive power can be adjusted in the range of -20% to +20% [4].

- **V/Hz Limiter**

(4) V/Hz limiter is provided in order to avoid over fluxing of the transformers. If the set point of the AVR is too high for a certain frequency, the set point will reduce smoothly according to a pre-adjusted V/Hz characteristic. The limiter becomes active after an adjustable delay time.

- **Soft-start**

(5) Soft start facility prevents overshoots of the terminal voltage when building up the excitation (field flashing). As soon as the excitation is switched on and after the initial field flashing is complete (approx. 10% of generator voltage), the soft-start-signal increases the machine terminal voltage with an adjustable gradient. This signal is given priority until its value exceeds the signal from the set point generator.

- **Automatic follow-up control**

In each Control Board (COB), including an Automatic Voltage Regulator (AVR) and a

Field Current Regulator (FCR), the automatic follow-up control ensures a bump-less changeover from automatic voltage control mode (AUTO mode) to the field current regulation (MANUAL mode). The change over may be initiated either by the loss of the PT’s measuring signal or by the operator (e.g.

from the Local Control Panel (LCP)). The difference signal derived from the control signals of the AVR and the FCR (Follow up block (6)) is used for the follow-up control of the regulator, which is not active. The follow upis guaranteed for both the AVR and FCR [4].

In a double automatic channel configuration the changeover is normally from AUTO mode of the active channel to the AUTO Mode of the stand-by channel. Indeed, any of channels may be active or stand-by. In case the change over to the AUTO Mode of standby channel is not possible, a change over to the MANUAL mode will be initiated. Only incase that both of channels are inoperable a trip command will be given. In this configuration the follow-up signal to the inactive channel is derived from the difference of the control signals of the active and inactive channels (Follow up block (7)) [4].

In a Single Channel and Back up control configuration the Backup Field Current Regulator (BFCR) automatically follows up the Control Board (COB). In case the Control Board (COB) fails the automatic follow-up ensures a bump-less changeover from the Control Board (COB) to the BFCR, i.e. to the field current regulation (MANUAL mode). As already mentioned the BFCR is a software function of the Extended Gate Controller (EGC) [4].

- **Limiter gates**

The limiter gates (8) and (9) determine the priority of the over excitation or under excitation limiters over the terminal voltage control. In order to avoid that two limiters are active at the same time (e.g. in case of system fault), a priority flag can be set choosing which of the limiter groups (over excitation or under excitation) acts first.

- **PID Controller**

The input voltage of the PID controller (11) represents the voltage error that is the difference between an actual value and a set point. The output of the PID controller, which is so called control voltage Uc, is required as an input signal for the gate control unit (12).

The feedback parameters of the PID controller are automatically adjusted in a way to achieve an optimum control performance of the synchronous machine. Depending on that, which limiter becomes active, the Parameter Selector (10) activates the appropriate set of PID parameters (SET1/SET2). This contributes to the transient stability of the synchronous machine [4].

2.4.2.3. Limiter Functions

The purpose of the limiters is to maintain the operation point of the machine within permissible limits and therefore to avoid its undesired shut-down by operation of the protective relays.

Figure 2.15 shows a typical power chart of a salient pole synchronous machine with the corresponding operation limits in steady state condition for 1 p.u. terminal voltage.

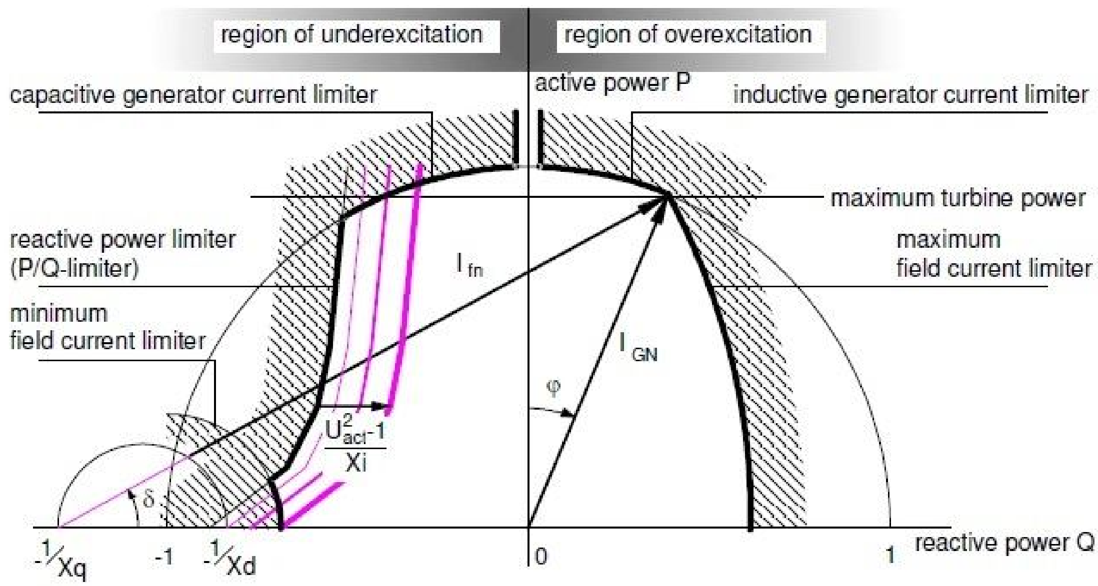


Figure 2.15: Power chart of a salient pole synchronous machine.

UNITROL 5000 excitation system provides the following limiter functions:

- **Over excitation limiters**
  - Maximum field current limiter (Figure 2.16)
  - Stator current limiter over excited (Figure 2.17)
- **Under excitation limiters**

– P/Q limiter (Figure 2.18)

– Stator current limiter under excited (Figure 2.17)

– Minimum field current limiter (Figure 2.16)

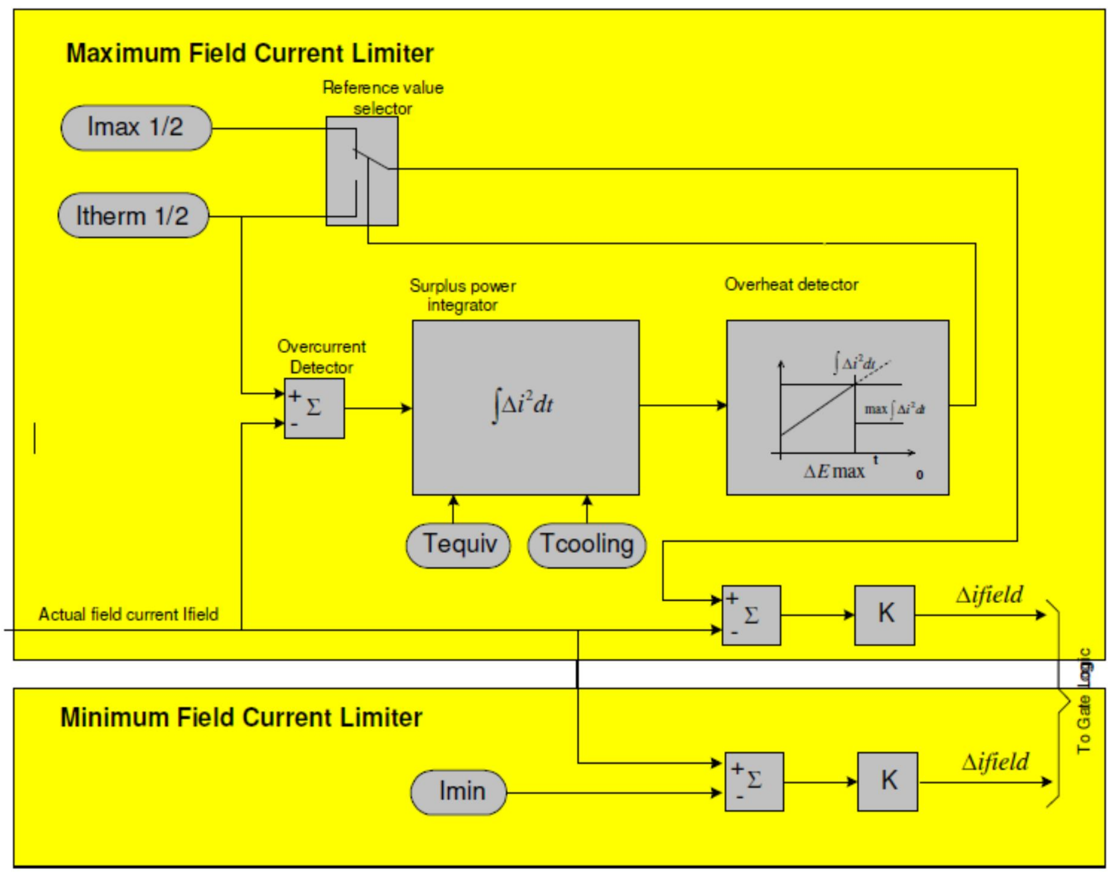


Figure 2.16: Maximum and Minimum field current limiters.

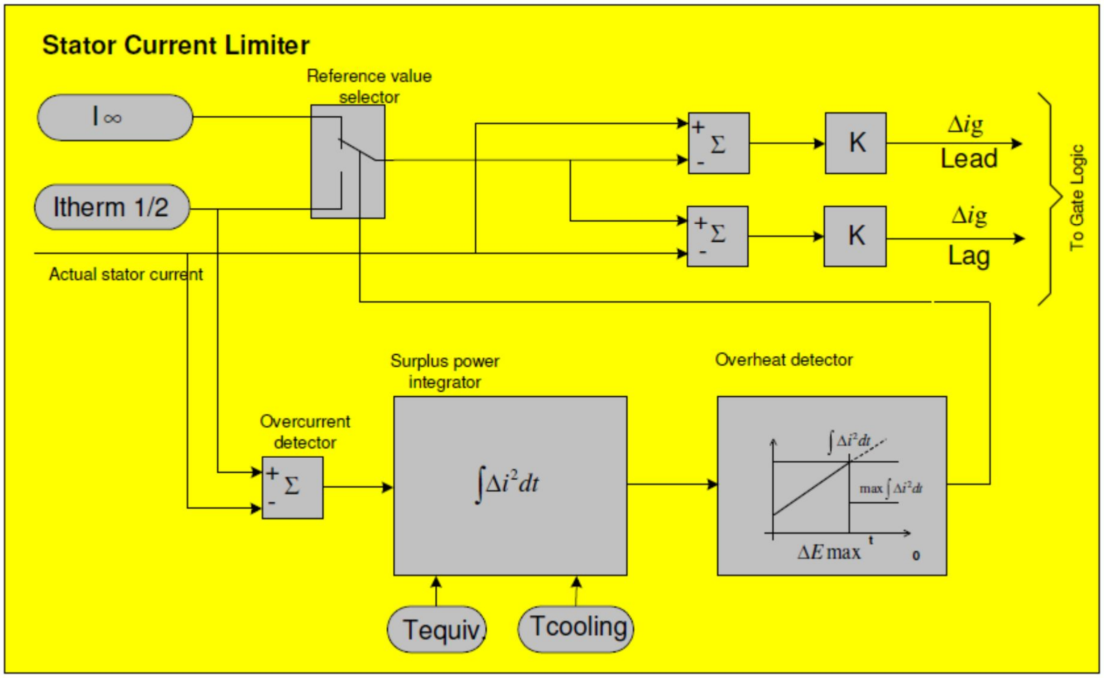


Figure 2.17: Stator current limiter for over and under excited mode of operation

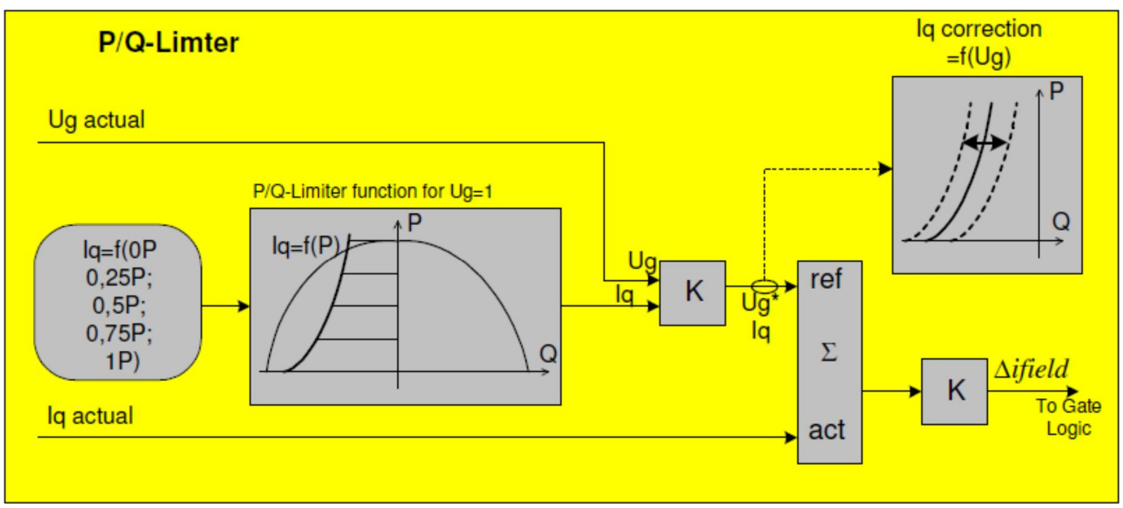


Figure 2.18: P/Q limiter.

CHAPTER THREE

EXCITATION SYSTEM MODEL

A physical model of the Excitation system has been created with Matlab/ Simulink/ SimPowerSystems toolbox. The simulation results from the model will be compared against measurements from the real system to see if they will give the same results. SimPowerSystems is a more powerful tool in modeling power systems .Instead of deriving, programming and solving dynamics equations of the system components, SimPowerSystems provides more detailed component blocks for modeling power systems components in the Simulink environment. In SimPowerSystems library, there are over 100 different blocks which including various power systems and electrical components. One of the most important advantages of this toolbox is that a SimPower systems model can be connected to a hydraulic or mechanical system for a multidomain simulation. Moreover, a SimPower Systems model closely resembles the excitation system schematic, which lets the user to understand and analyze the model much more efficiently.The SimPowerSystemsmodel is shown in figure (3.1) Most of the parameters of the SimPowerSystemsmodel blocks were extracted from the components datasheets.

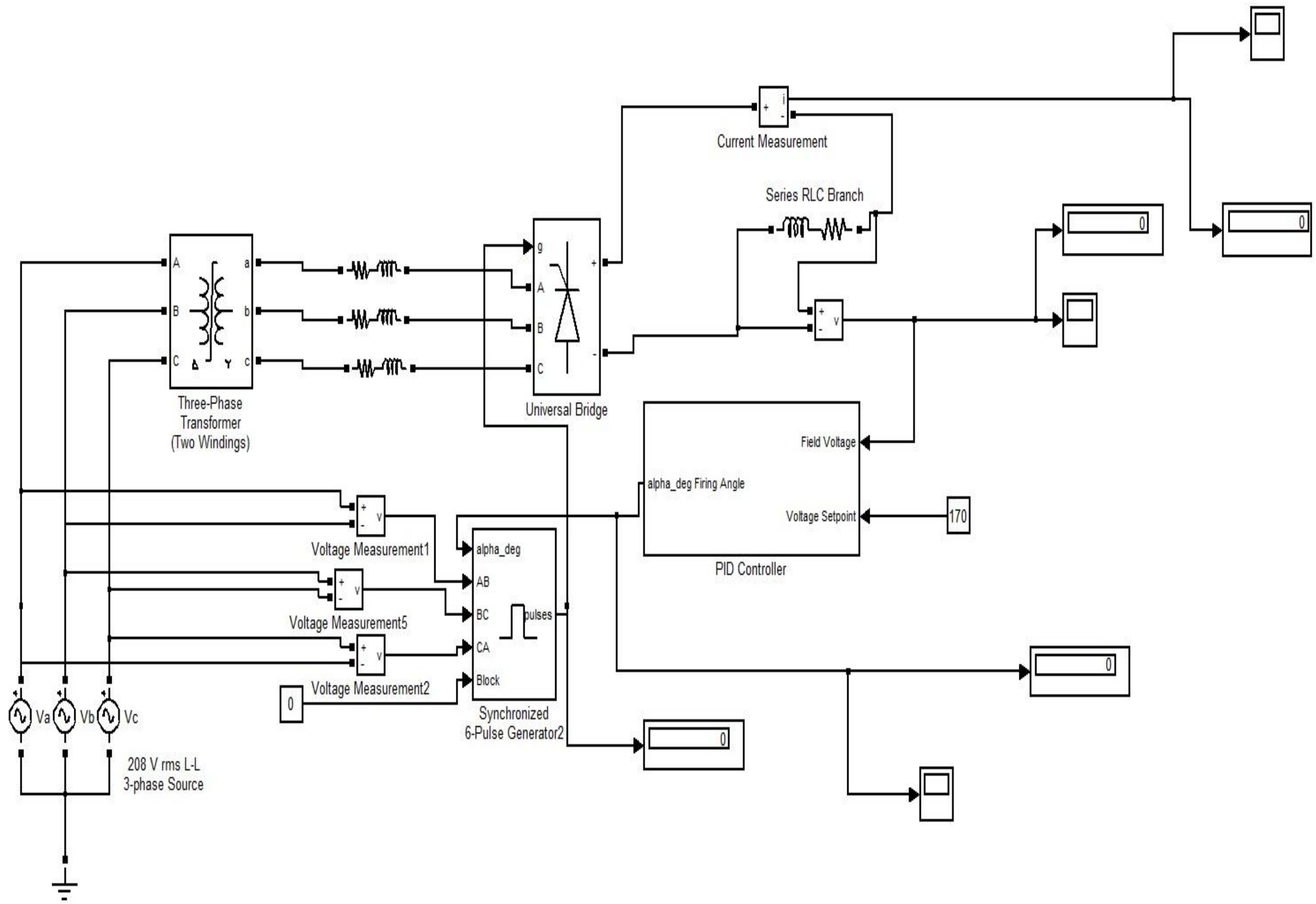


Figure 3.1: SimPowerSystems Model

3.1. Three phase Source model

The three phase source model represents the three phase output of the generator and it was modeled using the AC Voltage source block (see figure 3.2).

The AC Voltage Source block implements an ideal AC voltage source. The generated voltage U is described by the following relationship:

$$U = A\sin(\omega t + \emptyset) \quad (3.1)$$

Negative values are allowed for amplitude and phase. A frequency of 0 and phase equal to 90 degrees specify a DC voltage source. Negative frequency is not allowed; otherwise the software signals an error, and the block displays a question mark in the block icon. Figure 3.3 shows the parameters used in AC voltage source block [5].

3.2. Voltage measurement Model

The Voltage measurement model represents the VT at the output of the generator three phase and it was modeled using the Voltage Measurement block Voltage Measurement block. The Voltage Measurement block measures the instantaneous voltage between two electric nodes. The output provides a Simulink® signal that can be used by other Simulink blocks [5]. The Output signal specifies the format of the output signal when the block is used in a phasor simulation. The Output signal parameter is disabled when the block is not used in a phasor simulation. The phasor simulation is activated by a powergui block placed in the model. It can be set many parameters to get the desired output. Set to Complex to output the measured current as a complex value. The output is a complex signal. Set to Real-Image to output the real and imaginary parts of the measured current. The output is a vector of two elements. Set to Magnitude-Angle to output the magnitude and angle of the measured current. The output is a vector of two elements.Set to Magnitude to output the magnitude of the measured current. The output is a scalar value [5].

Excitation Transformer Model

The excitation transformer was modeled using the Three-Phase Transformer (Two Windings) block which implements a three-phase transformer with configurable winding connections (see figure 3.6).

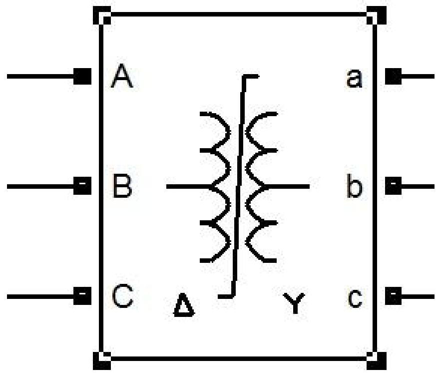


Figure 3.2: Three-Phase Transformer (Two Windings) block

The Three-Phase Transformer (Two Windings) block implements a three-phase transformer using three single-phase transformers. You can simulate the saturable core or not simply by setting the appropriate check box in the parameter menu of the block. See the Linear Transformer block and Saturable Transformer block sections for a detailed description of the electrical model of a single-phase transformer. The two windings of the transformer can be connected in the following manner:

- Y
- Y with accessible neutral
- Grounded Y
- Delta (D1), delta lagging Y by 30 degrees
- Delta (D11), delta leading Y by 30 degrees

The two windings of the transformer was connected using Delta (D1) as in the real system.

The block takes into account the connection type you have selected, and the icon of the block is automatically updated. An input port labeled N is added to the block if you select the Y connection with accessible neutral for winding 1. If you ask for an accessible neutral on winding 2, an extra output port labeled n is generated. The saturation characteristic, when activated, is the same as the one described for the Saturable Transformer block, and the icon of the block is automatically updated. If the fluxes are not specified, the initial values are automatically adjusted so that the simulation starts in steady state. The leakage inductance and resistance of each winding are given in p.u. based on the transformer nominal power Pn and on the nominal voltage of the winding (V1 or V2). For an explanation of per units, refer to the Linear Transformer and Saturable Transformer block reference pages [5].

Parameters of Three-Phase Transformer (Two Windings) block are shown in figure 3.7.

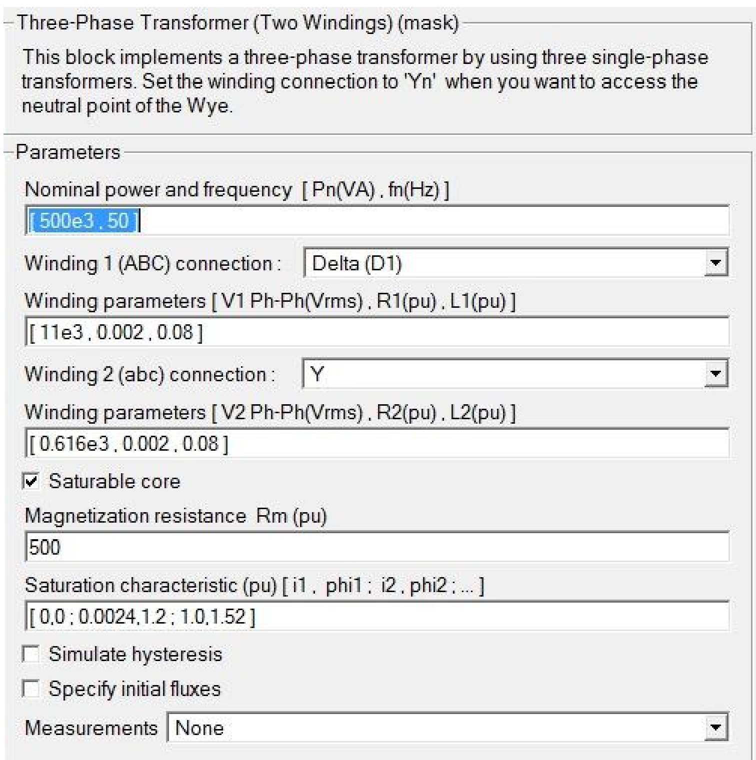


Figure 3.3: Parameters of Three-Phase Transformer (Two Windings) block

3.3. Convertor Model

The Converter was modeled using the universal bridge Block which can implement a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration. The type of power switch and converter configuration is selectable from the dialog box.

The Universal Bridge block allows simulation of converters using both naturally commutated (and line-commutated) power electronic devices (diodes or thyristors) and forced-commutated devices (GTO, IGBT, and MOSFET).

The Universal Bridge block is the basic block for building two-level voltage-sourced converters (VSC) [5]. The type of Universal Bridge used in this model is the thyristors as in the real system. Number of bridge arms: Set to 1 or 2 to get a single-phase converter (two or four switching devices). Set to 3 to get a three-phase converter connected in Graetz bridge configuration (six switching devices). Snubber resistance Rs: The snubber resistance, in ohms (). Set the Snubber resistance Rs parameter to inf to eliminate the snubbers from the model. Snubber capacitance Cs: The snubber capacitance, in farads (F). Set the Snubber capacitance Cs parameter to 0 to eliminate the snubbers, or to inf to get a resistive snubber. In order to avoid numerical oscillations when your system is discretized, you need to specify Rs and Cs snubber values for diode and thyristor bridges. For forced-commutated devices (GTO, IGBT, or MOSFET), the bridge operates satisfactorily with purely resistive snubbers as long as firing pulses are sent to switching devices. If firing pulses to forced-commutated devices are blocked, only antiparallel diodes operate, and the bridge operates as a diode rectifier. In this condition appropriate values of Rs and Cs must also be used [5]. When the system is discretized, the following formulas can be used to compute approximate values of Rs and Cs:

$$R_s > 2\frac{T_s}{C_s} \quad \text{(3.2)}$$

$$C_s < \frac{P_n}{1000(2\pi f){V_n}^2} \quad \text{(3.3)}$$

These Rs and Cs values are derived from the following two criteria:

- The snubber leakage current at fundamental frequency is less than 0.1% of nominal current when power electronic devices are not conducting.
- The RC time constant of snubbers is higher than two times the sample time Ts. These Rs and Cs values that guarantee numerical stability of the discretized bridge can be different from actual values used in a physical circuit.

3.4. Rotor DC current measurement

Rotor DC current measurement was modeled using the current measurement block and it parallels the CT in the real system .The Current Measurement block is used to measure the instantaneous current flowing in any electrical block or connection line. The Simulink output provides a Simulink signal that can be used by other Simulink blocks In this model the output parameter was set to complex .

3.5. Pulse Generator Model

The pulse Generator is a part of the COB which output pulses for the CIN and then to the GDI of the thyristor converter. The pulse Generator was modeled using Synchronized 6-Pulse Generator which implements a synchronized pulse generator to fire the thyristors of a six-pulse converter.

The Synchronized 6-Pulse Generator block can be used to fire the six thyristors of a six-pulse converter. The output of the block is a vector of six pulses individually synchronized on the six thyristor voltages. The pulses are generated alpha degrees after the increasing zero crossings of the thyristor commutation voltages [5].

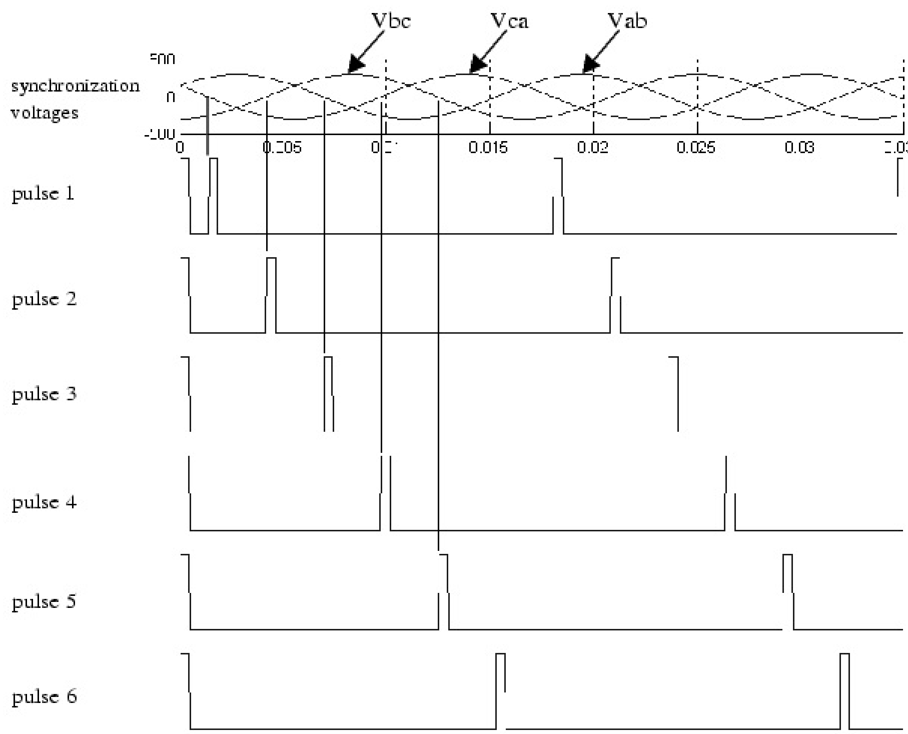


Figure 3.12: Synchronization of the six pulses for an alpha angle of 0 degrees

The Synchronized 6-Pulse Generator block can be configured to work in double-pulsing mode. In this mode two pulses are sent to each thyristor: a first pulse when the alpha angle is reached, then a second pulse 60 degrees later, when the next thyristor is fired. Figure 3.13 below display the synchronization of the six pulses for an alpha angle of 30 degrees and with double-pulsing mode. Notice that the pulses are generated 30 degrees after the zero crossings of the line-to-line [5].

3.6 The PID Controller Model

The PID Controller Model was modeled using the PID Controller subsystem as in figure 3.16.

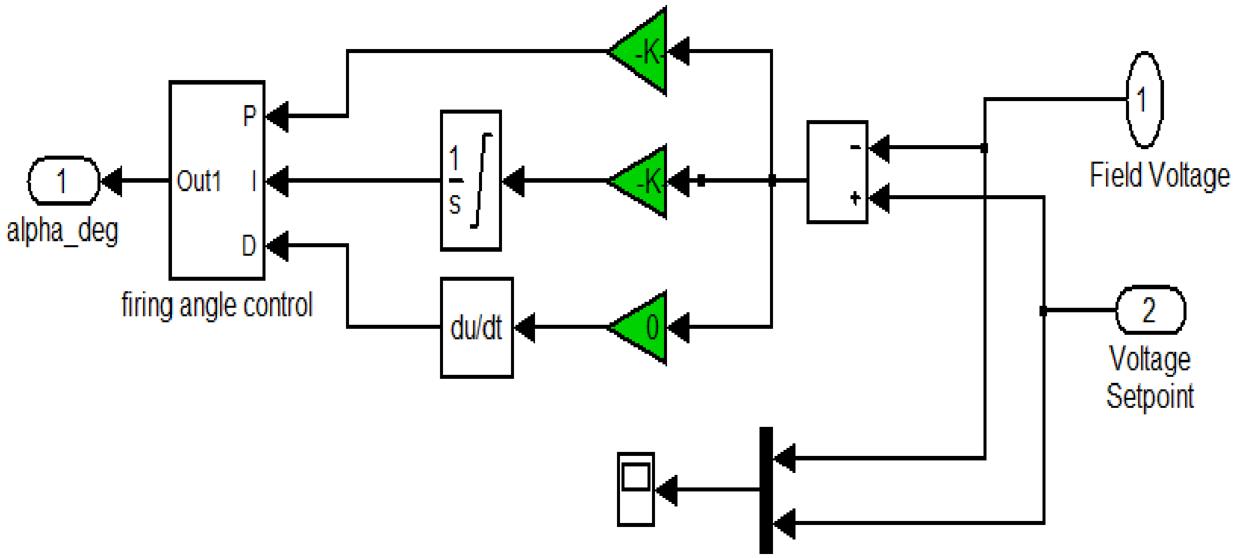


Figure 3.16: PID Controller subsystem

The range of firing angle is specified to be up to (150 deg) same as built in the existing system, and in order to control the (DC) output voltage, Proportional integral derivative method was used, which is also incorporated in the control algorithm of the existing ABB unitrol5000, to control the firing angle required to trigger a three phase thyristor converter. Nickolas-Ziegler method is used for tuning the PID gains necessary to reach the desirable stability band.

3.7 Exciter Mathematical Model

the establishing the missing dynamic link between the field voltage vf and the synchronous generator terminal voltage |V|. Considering the field of the synchronous generator, giving:

Δvf = Rf Δif + Lf f dt/d* (Δif) ...………………………........………. (3.4)

Taking Laplace transform

$\Delta v_f\ (s)\ =\ [R_{-f}\ +\ s\ L_{ff}]\Delta i_f$ (s)... (3.5)

As the terminal voltage equals to internal emf minus the voltage drop across the internal impedance, it is clear that the relationship between vf and |V| depends on the generator loading. The simplest possible relationship exists at low or zero loading in which case V approximately equals to internal emf E. In the generator, internal emf and the field currents are related as [6]

$E\ =\ (\omega L_{fa} * i_f)/\sqrt{2}$ .... (3.6)

Here L_{fa} is the mutual inductance coefficient between rotor field and stator armature.

Δif =$\sqrt{2} * \frac{E}{\omega L_{fa}}$ .... (3.7)

Laplace transform of above eq. gives

Δif (s)= $\sqrt{2} * \frac{E}{\omega L_{fa}}$ (S)... (3.8)

Substituting the above in eq. (3.7),(3.8), $\Delta v_f(s)\ =\ [R_f\ +\ sL_{ff}]\Delta i_f(s)$ results in

$\Delta v_f(s)\ =\ \sqrt{2}/\omega l_{fa}\ [\ R_f\ +\ s\ L_{ff}]\ \Delta E\ (s)$ ....(3.9)

Thus $\Delta E\ (s)\ =\ (\omega L_{fa})/\sqrt{2} * 1/(R_f + sL_{ff})\ \ \Delta v_f\ (s)$...........................(3.10)

From the above equation. the field voltage transfer ratio can be written as

$\frac{\Delta E(s)}{\Delta V_f(s)} \approx \frac{\Delta V(S)}{\Delta V_f(s)} = \frac{\omega L_{fa}}{\sqrt{2}} * \frac{1}{R_f + sL_{ff}} = \frac{K_f}{1+sT_{do}}$.. (3.11)

Ware

$$K_f = \frac{\omega L_{fa}}{\sqrt{2} * R_f} \quad \text{and} \quad T_{do} = \frac{L_{ff}}{R_f} \qquad \text{...(3.12)}$$

CHAPTER FOUR

SIMULATION AND RESULTS

In Chapter 3, excitation system model was developed. The objective of this chapter is to verify the model experimentally. For verification, measured variables on the real system will be compared with simulation results.

In this study, measurements are done directly on the real excitation system and measured variables are:

- Excitation voltage at no load in Volts.
- Excitation current at no load in Amps.

Furthermore, the frequency response of the model will be analyzed and the linear model is obtained using the linearized frequency response data.

The first order system transfer function parameter is compared to the real plant response.

4.1. Step response comparison

Figures 4.1 and 4.2 show the step response of voltage and current at no load respectively. As mentioned before, Rosiers Power Plant consists of seven units, so unit 4 was taken as sample and its step response was obtained from the trends of POS clients in the CCR.

Table 4.1: Comparison between Simulation and Experimental Results

Results	Field Voltage (Volts)			Field Current (Amps)		
	Experimental	Simulation	Error %	Experimental	Simulation	Error %
Steady State Value	134	132	1.5	391	412	5.4
Peak Overshoot Value	176	150	14.8	398	462	16.08

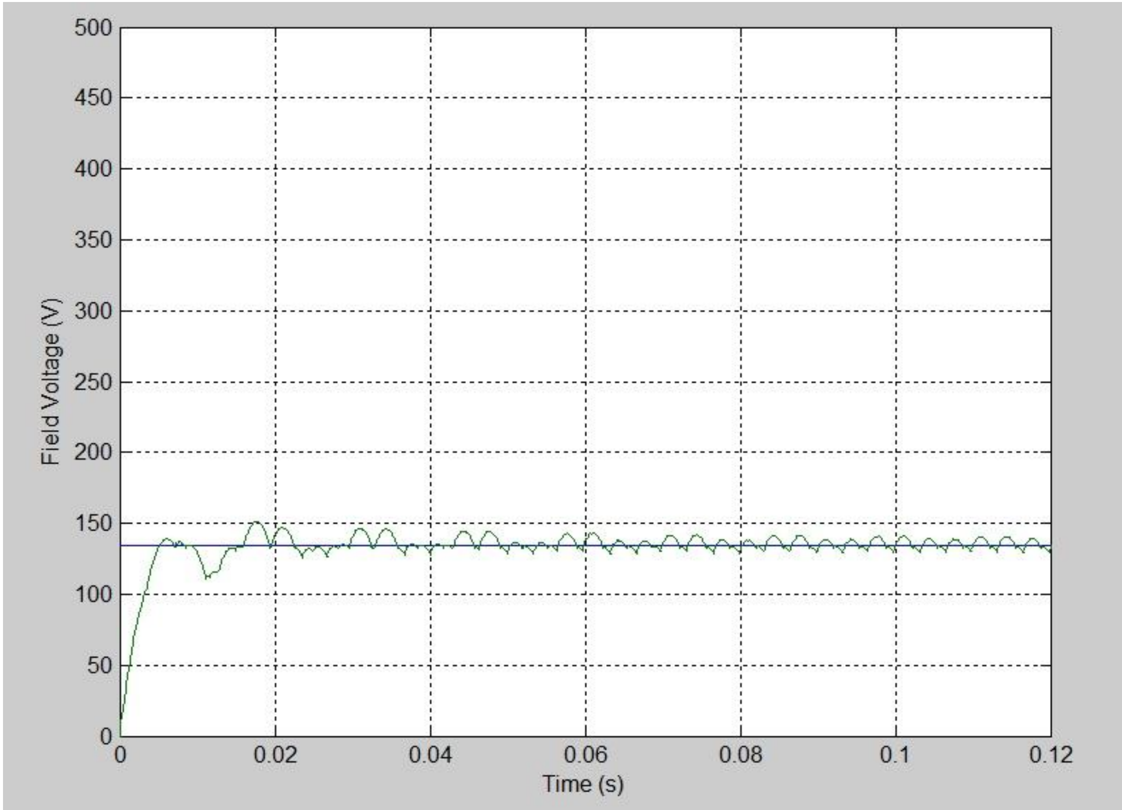


Figure 4.1: Field Voltage step response

It can be seen from table 4.1 that the model step response conforms to the real system step response which is found in Appendix A.

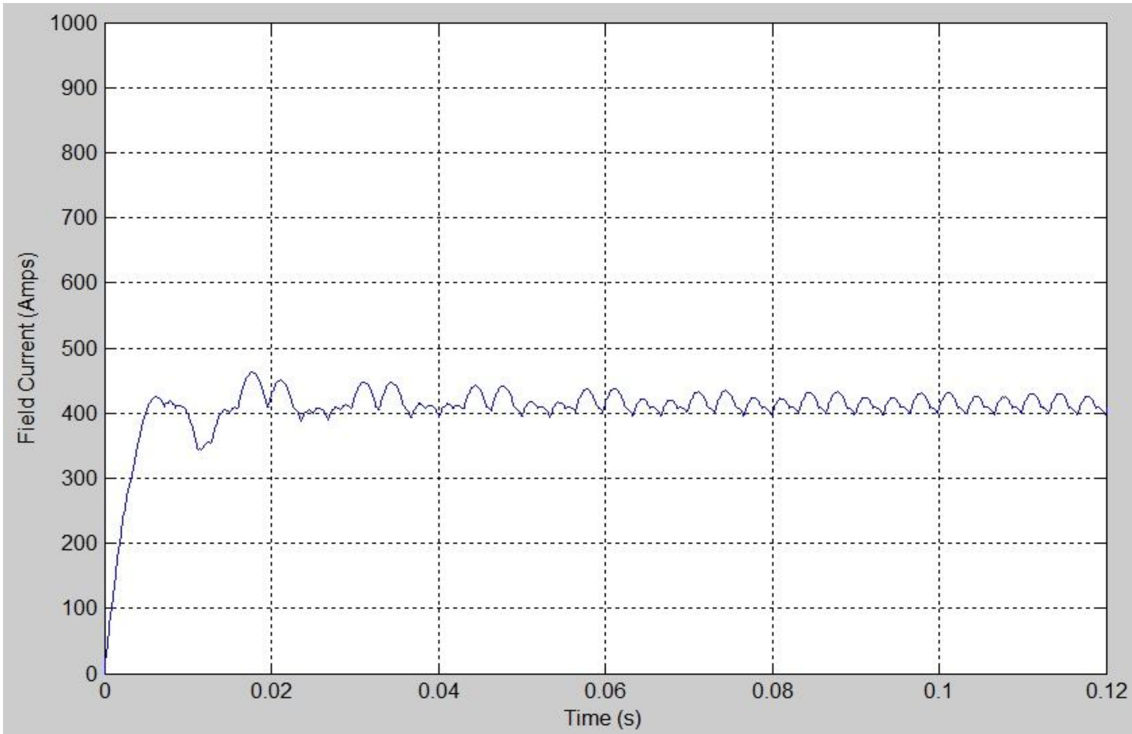


Figure 4.2: Field Current step response

4.2. Closed loop Frequency response:

In order to identify the excitation model characteristics, a closed loop frequency response has been carried out, using sine sweep chirp signal start frequency sweep from 0.1 Hz up to 100 Hz. The model response data has been sampled over a period of 2 sec, using sampling frequency of (1000Hz). The resulting data of the inputs and out puts are saved to MATLAB work-space.

In order to get the magnitude and phase of the model response, FFT method is used with the same sampling frequency, sweep frequency range and time interval of 2 sec an M-file containing the code for calculations of (FFT) is attached in appendix (B).

The resulting plots are shown in figure 4.3.

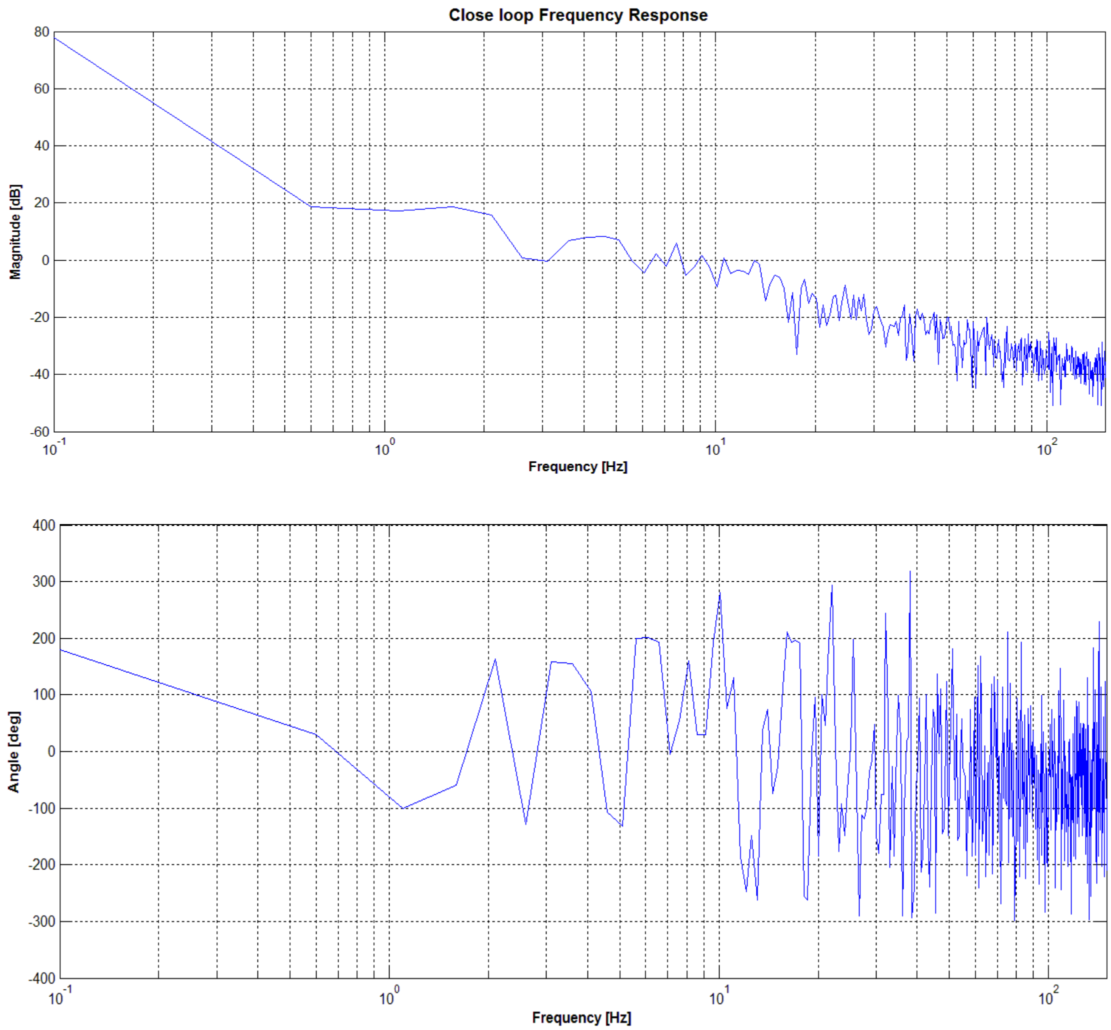


Figure 4.3: Closed Loop Frequency response

The built in basic fitting function in matlab is used to linearize the frequency response characteristics [see fig 4.4], from the it is clear that frequency corresponding to -3 dB point is about (11 Hz), which approximately matches the cut off frequency given by (R/L) about 12.3 Hz for the rotor winding, this fact verifies that the band width of the exciter is dominated to some extent by the characteristics of the generator rotor winding. The deviation in band limit is a bout (9.7%), which is due to commutation impedance which affects the thyristors switching speed, and thus the overall performance of the system.

However, the non-linear model response is not consistent with the linearize model response at higher frequencies. This is the result of linearization, with the increasing excitation frequency the operating points where the linearization is performed changes.

To obtain the transfer function, we proposed a second order approximation for the system; the linearized model response shown in [fig 4.4] is used as follow:

From the figure maximum overshoot is about 6.31 dB giving amplitude ratio of M = 2.06. The cut off frequency is read from the -3dB which is 11 Hz, so the transfer function H(s) is:

$$H(s) = \frac{k}{S^2+2\xi\omega S+\omega^2} \quad \text{.. ..... (4.1)}$$

Where:

ω_n: is the system cutoff frequency =11 Hz

K: is the system gain.

ξ: is the damping factor, which can be calculated using the relation between it and the maximum overshoot (M) as follow:

$M = e^{[-2\xi/\mathrm{root}\ (1-\ \xi\ 2]}$

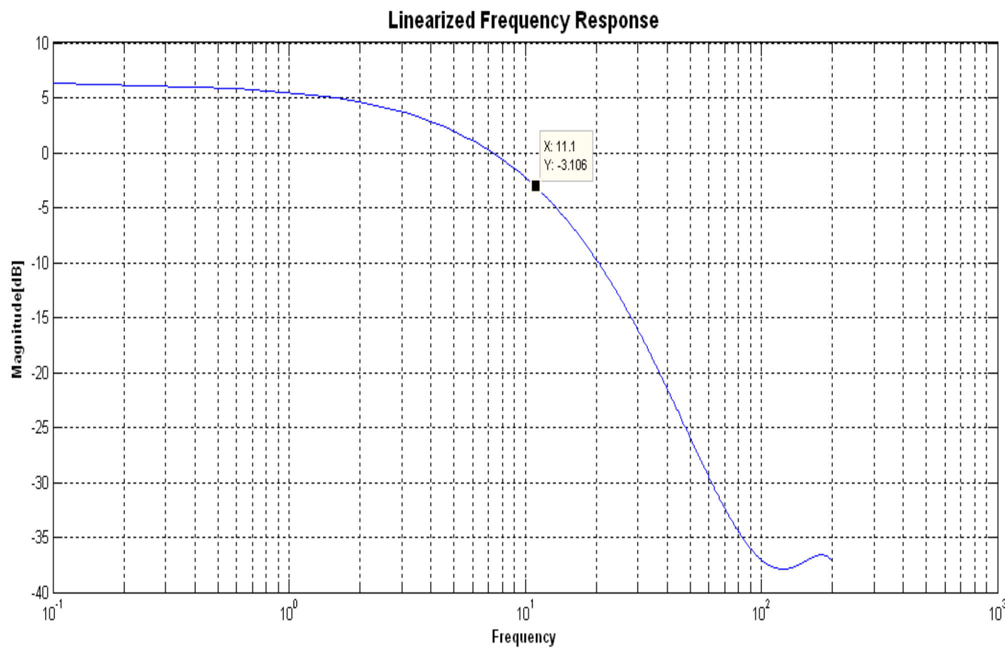
ξ = root (M^2/ [4+M^2]) .... (4.2)

And it is found to be 0.47 .The transfer function gain (K) is taken to be equal to the system gain of (2.06/ ω_n^2) so the resulting transfer function is:

$$H(s) = \frac{0.02}{(\mathbf{0.0083}S^2 + 0.0855S + 1)} \quad \text{...} \quad (4.3)$$

From the transfer function it is clear that the system tends to behave as integrator, because the second order term has very small effect on the transfer characteristics, so the system is reduced to a first order with the following transfer function:

$H(s)_{1^{st}\text{-order}} = 0.02/0.0855S+1$. 4.4



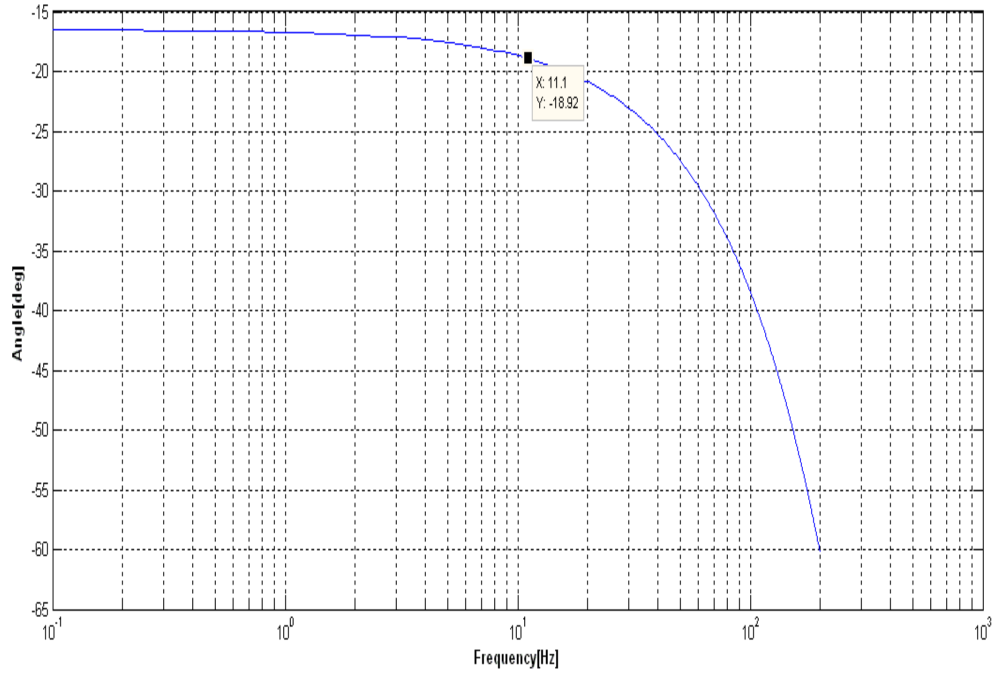


Fig 4.4: Linearized Frequency Response of the Model

We can see from fig 4.4, the time constant of the first order approximation (τ =0.0855), is an important parameter, because at time t= τ, the response of the system reaches 63.2% of its total change. This can be verified from the linearized system response shown in fig 4.5, at time 0.0855 sec the system response is (85.884 volt) about 63.15% of 136 volt. On the other hand the parameter (1/ τ) equal 11.7 approximates the band width of the linear system mentioned above.

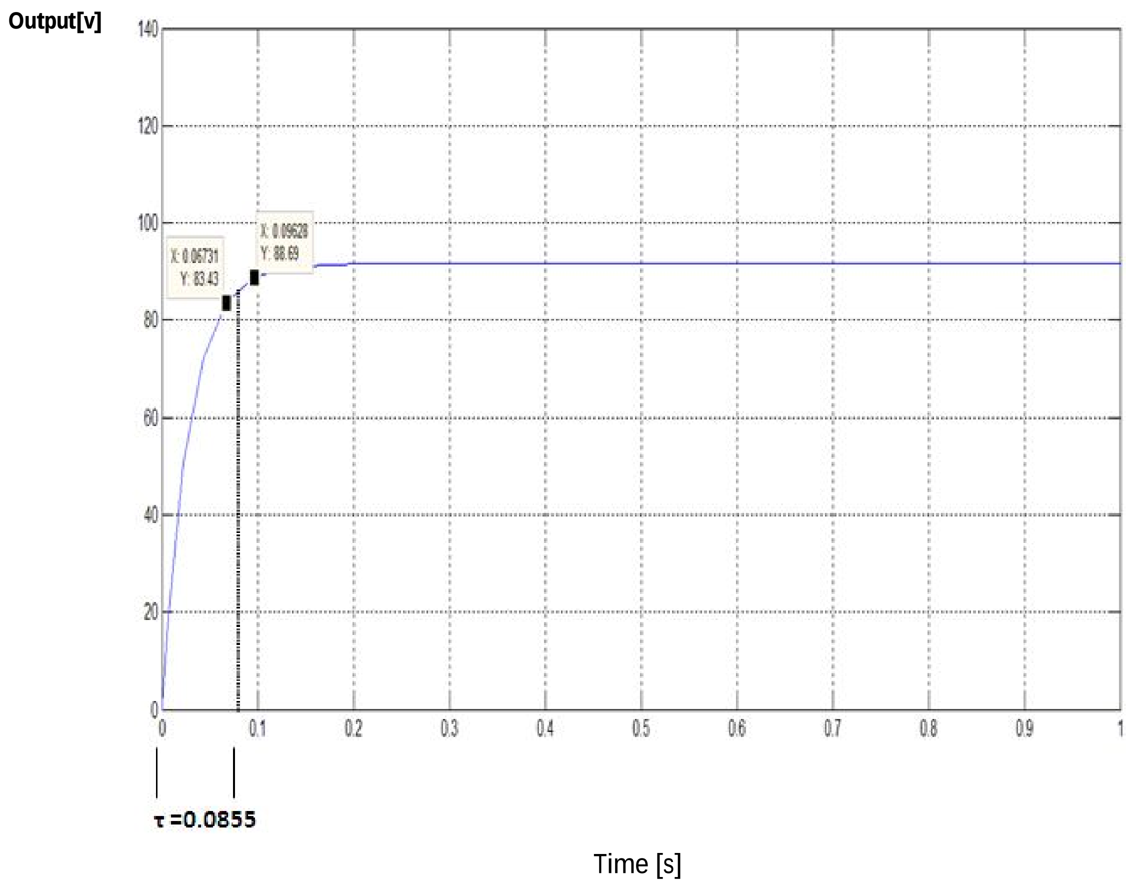


Fig4.5: Equivalent first order system response

CHAPTER FIVE

CONCLUSION AND RECOMENDATION

5.1. Conclusion:

This research, a detailed description for the following topics is presented:

- The functions and performance requirements of excitation systems in general.
- The structure and type of excitation systems is presented,
- A description of the existing excitation system in Rosaires Hydro Power Plant presented in chapter two.
- In chapter three, a detailed description of a three phase source, voltage measurement, and excitation transformer models.
- Also, structure of models for the converter block, rotor current measurement, pulse generator and firing angle controller is detailed.
- In chapter four, a step response is carried out to determine system stability characteristics.
- Also in this chapter, a closed loop frequency response is carried out using sine sweep signal(chirp signal) as input to estimate the stability bandwidth and to determine the linear model of the excitation system.

5.2. RECOMENDATION

We recommend a double channel excitation system, which consists of two converter units operating in parallel. Each converter supplying 50% of the rotor field current and capable of supplying the rotor rated field current compared to the single converter this type will facilitate the following advantages:

- If one converter tripped the other will take the load without any disturbance to the generator terminal voltage.
- No need for complete unit shutdown to maintain excitation system.
- Increase of converters life time due to partial loading.
- Enhancement of system overall response.

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APPENDICES

APPENDIX A

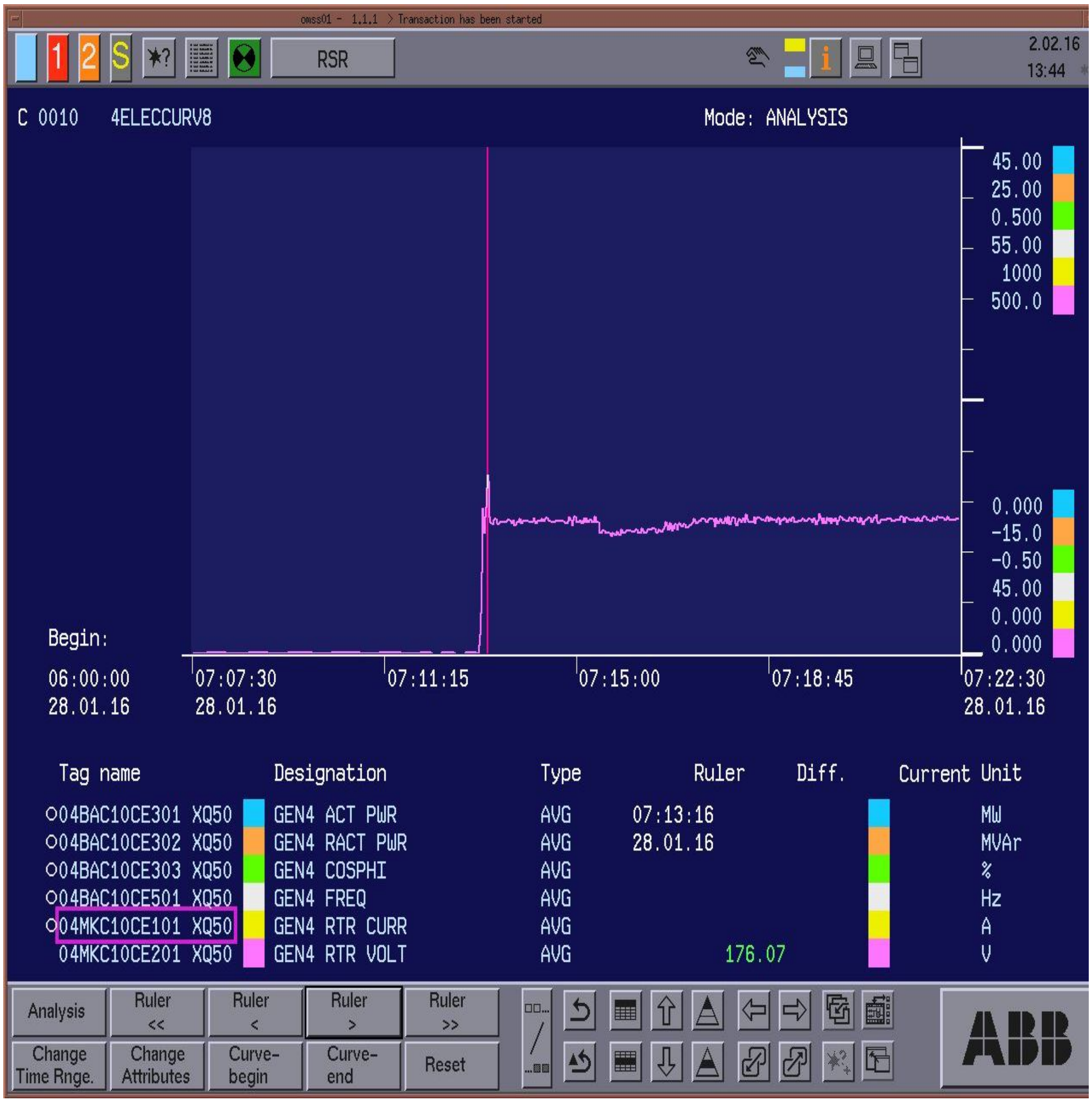

Figure A-1: Field voltage Peak overshoot value from POS client for real system

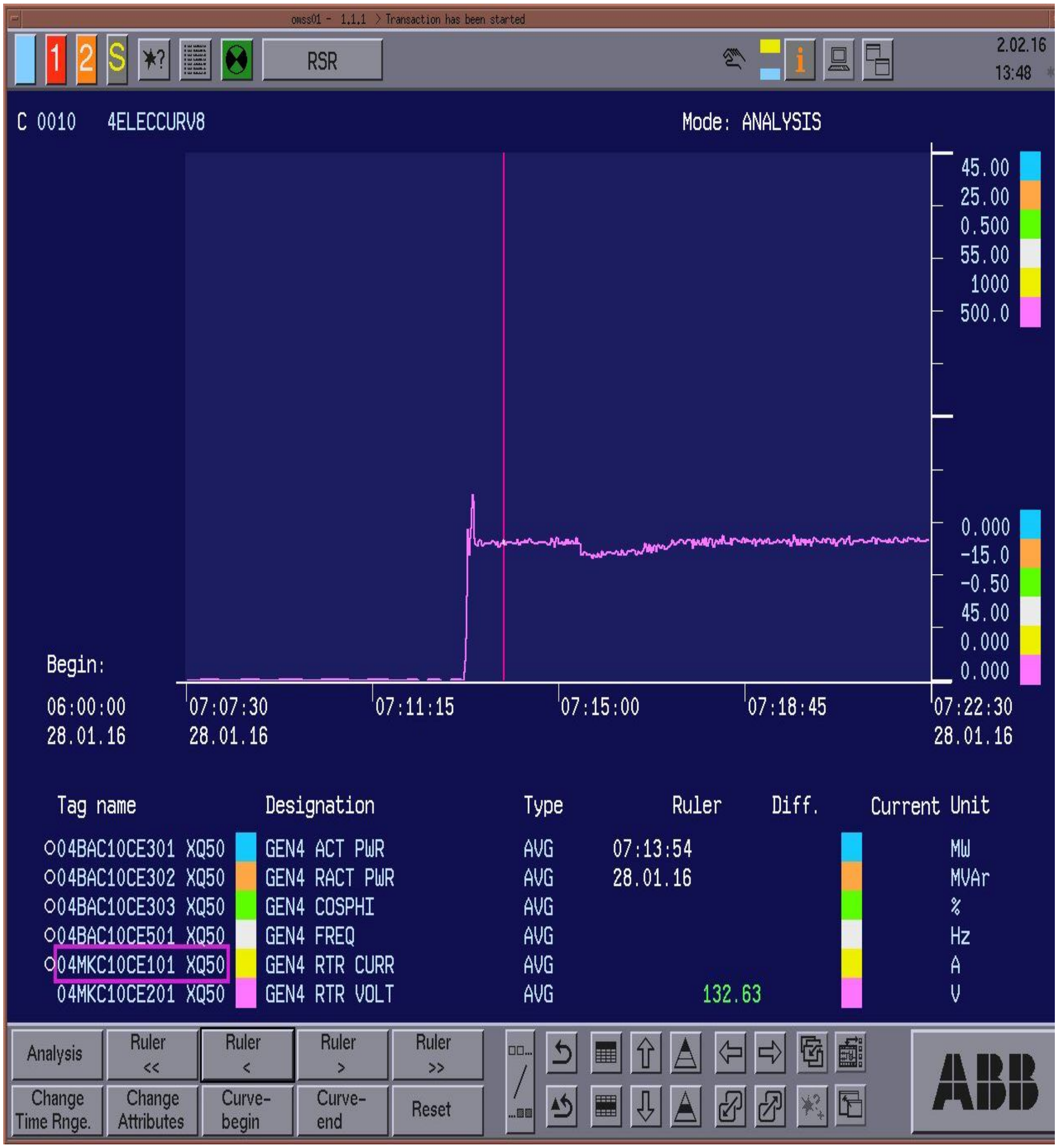

Figure A-2: Field voltage steady state value from POS client for real system

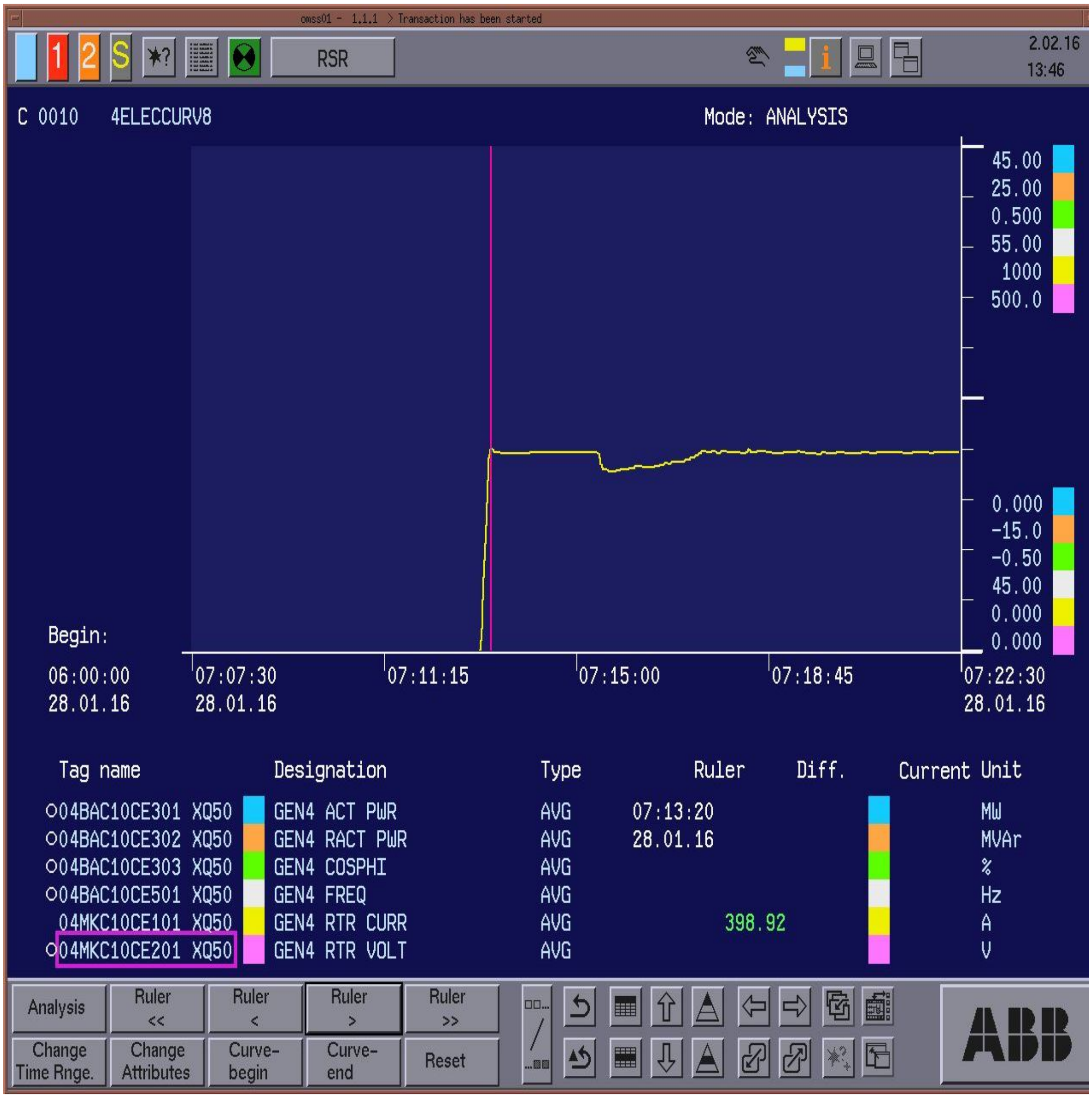

Figure A-3: Field Current Peak overshoot value from POS client for real system

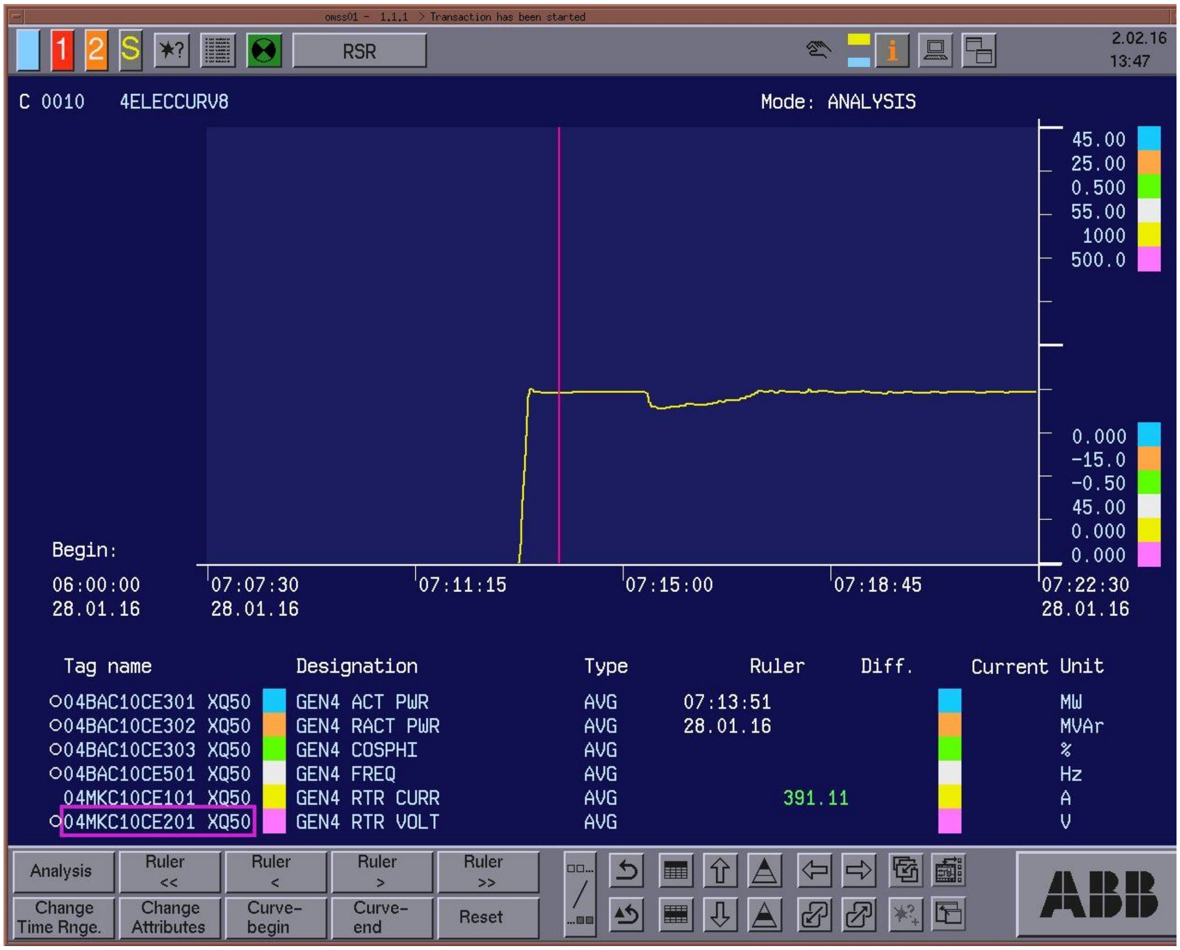

Figure A-4: Field current steady state value from POS client for real system

APPENDIX B

MATALB m-files

```
Pos(:,1)= vout;

Sp(:,1)= vin; % Reference Position

%%

fs=1000; % Sampling Rate [Hz]

tstart=0.1; % Start Time [s]

tend=2.1; % End Time [s]

FreqMin=0.1; % Minimum Frequency [Hz]

FreqMax=3.1; % Maximum Frequncy [Hz]

Freq_Inc=0.049975012; % Frequency Increment [Hz]

for i=1:1

   out(:,i)= Pos(:,i);

%in(:,i)=input(tstart*fs:tend*fs,i);

% Remove the 'linear' trend of the output

%out(:,i)=detrend(out(:,i));

% Calculate the FFT of the input and the Output

in_fft(:,i)=fft(Sp(:,1));

out_fft(:,i)=fft(out(:,i));

end

in_fft(:,1)=fft(Sp(:,1));

% Take the Avarage FFT

for i=1:length(out_fft)

   out_fft_mean(i,1)=mean(out_fft(i,:));

 in_fft_mean(i)=mean(in_fft(i,:));

end

t=0:1/fs:(tend-tstart);
```

```
% Frequency Array

FreqArray=0.1:fs/(length(in_fft)):fs;

%% Bode Plot

Mag=20*log10(abs(out_fft_mean)./abs(in_fft));

PhsAngle=(-angle(in_fft)+angle(out_fft_mean))*180/pi;
```