UNIVERSITY OF
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College of Agriculture, Engineering and Science

GENERATOR EXCITATION CONTROL AND COORDINATION FOR PROTECTION

By

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In fulfillment of the Master of Science in Electrical Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal.

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Publication 1
DN Ngema, AK Saha, "Coordination between Overexcitation and Generator Over-voltage Protection with respect to Overexcitation Limiters", 24th Southern African Universities Power Engineering Conference, pp 391-396, 26-28 January 2016, Vereeniging, South Africa.

Publication 2
DN Ngema, AK Saha, "Simulation Study of Generator Under-excitation Operation and Under-excitation Limiters", 24th Southern African Universities Power Engineering Conference, pp 299-304, 26-28 January 2016, Vereeniging, South Africa.

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Abstract

The operation of a generator may easily be affected by faults within the machine itself as opposed to external disturbances occurring on the network to which it is connected. Generator protection must therefore be designed to react efficiently in both conditions. This thesis is a research based modeling, simulation and testing of generator excitation system control and protection. Real time digital simulator is employed in the simulation studies conducted as well as a commercial generator protection relay for hardware in-loop testing. The generator model used allows the user to model an excitation system separately for testing of internal faults; this enables excitation system limiters to be embedded in the automatic voltage regulator system model. Under and over-excitation limiters have been modeled and tested under different case studies conducted to study the system behavior and to ensure proper coordination with protection relays. These case studies are done using a software generator relay and the results are verified through hardware in-loop testing. The excitation limiters modeled and tested include straight-line characteristic under-excitation limiter which allows under-excitation operation case studies and two over-excitation limiters which are tested in the over-excitation region. Detailed representation of results based on different case studies conducted is entailed in the thesis. The results demonstrated confirm theoretical aspects based on different literatures reviewed as well as methodologies employed in testing excitation limiters with protection of generators for coordination. The generator protective functions studied are the ones closely coordinated with respect to excitation limiters and are employed to protect the generator. From the set of results obtained, it has been shown that excitation limiters prevent the generator from operating in operation zones that are thermally dangerous to the machine. When a major disturbance occurs in a power system, it is expected that generators help the system to return to a stable condition. However, for this to happen generators must remain synchronized and be operated within their capability limits, this has hence encouraged the coordination and control studies conducted in the dissertation.

Contents

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List of Symbols

Acronyms

RTDS	Real-Time Digital Simulator
AVR	Automatic Voltage Regulator
PSS	Power System Stabilizer
CT	Current Transformer
VT	Voltage Transformer
AC	Alternating Current
DC	Direct Current
HV	High Voltage
MEL	Minimum Excitation Limiter
MXL	Maximum Excitation Limiter
OEL	Over-Excitation Limiter
UEL	Under-Excitation Limiter
V/Hz	Voltage to Frequency Ratio
PDSM	Phase Domain Synchronous Machine
HIL	Hardware In-Loop

1. CHAPTER 1- Introduction

1.1. Introduction

Power systems protection is an important aspect in power generation, transmission and distribution. The protection of generators is vital because the generators are very large and expensive machines that produce very high voltages and are linked with other equipment such as prime movers, excitation systems, voltage regulators and they are also the single most important equipment required for electrical energy. Therefore it is also important to consider such equipment when designing protection systems such as relays. The objective of protection relays is to isolate the faulted section of the power system within the shortest time possible. This chapter entails fundamental background, feasibility study, objectives and the motivation behind the work conducted.

1.2. Research problem and motivation

Power system networks including generators are susceptible to disturbances occurring internally and externally. Severe range of damages may result due to misoperation in control and protective functions. The idea is to ensure that each power system equipment failure does not affect other neighbouring equipment. A part of ensuring the network's safety, stability and reliability is by ensuring that the stability control and protection of the system is adequate. With appropriate operation of power system controls such as circuit breakers, generator excitation controls; the power can regain stability before any damage to the system. Generator protection services employed in many utilities allows [1];

- Sufficient sensitivity and the timely tripping of the faulted portions of the network under fault conditions
- Prevention of tripping under no fault conditions
- Discrimination and grading for backup functions during fault conditions

The protection functions are not only limited to the above mentioned but also include generator capability control. Within the scope of generator excitation control and protection, it is very important that these two be coordinated adequately to provide full protection. Detailed real-time models are developed to carry out hardware-in-loop studies for particular generator protection elements related to the studies conducted. The phase-domain synchronous machine model is utilized for the simulation studies. The validity of testing a commercial generator protection relay using the phase-domain synchronous machine model is established. The focus is mainly on coordination of generator protective functions with respect to excitation limiters in the underexcitation and overexcitation region. These coordination studies particularly help to provide generators with excitation control; capability limits control, primary and backup protection enhancing the stability of the power system. In that way, the power system network is fully protected from faults.

1.3. Research questions

The key questions to be addressed:

- How do excitation limiters operate to keep the generator within capability limits?
- Which protective functions are monitored in the over and underexcitation regions?
- Should the limiters fail to operate, what are possible consequences?
- How are excitation limiters coordinated with protective functions to provide full protection against internal and external faults?

1.4. Background

Generators are designed to operate for a number of years; this may result in abnormal working conditions as the generator ages [1]. The generator and its auxiliaries are monitored by devices that minimize the occurrence of incidences leading to abnormal working conditions. Despite the monitoring, electrical and mechanical faults may still occur. Therefore, it is of great importance to provide generators with protection equipment that will quickly initiate an isolation of the machine from the system in case of a fault and if necessary, a complete shutdown be initiated. There are many different types of faults that synchronous generators may experience and each one of them requires its specific type of protection. These may include but not limited to: phase instantaneous overcurrent (50P), neutral instantaneous (50N), phase time overcurrent (51P), neutral time overcurrent (51N), stator ground fault (64), generator breaker failure, loss of field excitation (40), thermal overload, loss of prime mover (32), loss of synchronism, under voltage, overvoltage (59) , negative sequence (46), Voltage per hertz (24), etc.[2].

The generator protective relaying technology has progressed from discrete electromechanical relays and static relays to digital multifunction protection systems. Most protection schemes in service today are discrete electromechanical or static relay types that have a history of providing reliable protection and continue to be applied in many applications. However, with the availability, additional performance, economic advantages, and reliability of digital multifunction protection systems, this technology is being incorporated into most new protection schemes [3]. In the past, the malfunctioning of one multifunction generator relay would result to severe consequences because one relay incorporated different protection functions. However, this could easily be resolved through proper planning ensuring that each relay is on service [2]. Excitation system control plays a vital role in protection studies. This involves the functioning of excitation limiters with automatic voltage regulators (AVR). Many excitation systems are now equipped with such control functions and they have shown better overall protection when coordinated with protection relays. In the past, some power system networks were equipped with manual voltage regulators which made it difficult for utilities to use excitation limiters. However; in modern power systems, AVR mode of operation is employed and this has made it relatively easy to employ excitation limiters in power system networks.

The limiters have shown the ability to ensure that generators operate within their capability limits during deviation in system parameters.

1.5. Thesis feasibility study

Generators do not have the same level of protection. Large machines will have the greatest number of different protective systems. This is due to the fact that serious damage to these units can be very costly, both in terms of repairs and also the cost due to the unavailability of the unit [7]. As a general rule, the larger the machine is, the more expensive its protection scheme is. Multifunction generator relays are designed to provide a high level of protection at moderate costs which allows engineers to design effective protection systems with minimum cost concerns. [4].

To avoid misoperation during system disturbances, protection relays should be adequately coordinated so as to maintain the stability of the power grid. Two blackout disturbances that occurred in 1996 western area and 2003 east coast has encouraged the need for proper coordination of generator protection functions and control [5]. Although generator protection plays a vital role in power system studies, sometimes it is not necessary to isolate a generator out of service during a disturbance. Excitation control is of great importance in terms of controlling generator excitation system parameters and with proper coordination with protection relays, overall system protection is adequate. The idea behind coordination of controls with protection is to allow time between operation of excitation limiters and protection. Excitation limiters are modelled and set to operate prior the generator relay during any disturbance. Should the limiters fail to operate, it is then that the relay will start operating and isolate the system under fault.

1.6. Thesis objectives

Generator protection scheme is used in power systems to protect individual parts of the generator connected to power system networks. The protection of generators is important because the generators are very large and expensive machines that produce very high voltages and are linked with other equipment such as prime movers, excitation system voltage regulators, cooling systems etc.[1]. As a result the protection of a generator considers individual generator components as well as equipment connected to it.

The performance of many protection relays can, and has been, successfully evaluated by conducting hardware-in-loop testing using a real-time simulator. However, the performance of some generator protection elements could not previously be evaluated in this way due to certain limitations of the mathematical approach normally used for dynamic modelling of synchronous machines in simulation programs. A recently-developed phase-domain synchronous machine model has the ability to represent internal winding faults on the stator circuit of a generator as well as a detailed electrical circuit representation of the generator’s excitation input [6].

The aim of this thesis is to carry out a thorough research-based analysis of the phase domain synchronous generator model and its application in generator protection and control studies using a commercial protection relay.

The objective of this research is to gain knowledge on the operating and the limitations of this generator model. Furthermore, the thesis is aimed at achieving coordination in the following areas:

- Coordination UEL with steady state stability, loss of field excitation (40) and under voltage (27) protection.
- Coordination of V/Hz limiter with overexcitation (V/Hz) protection.
- Coordination of over excitation limiter (OEL) with overexcitation (V/Hz) (24) and over voltage (59) protection.

1.7. Thesis layout

This thesis entails seven chapters. Chapter one entails an introduction to the work, principles used, background, motivation behind the work and questions relevant to the research work.

Chapter two provides theoretical aspects of generator protection and excitation control. Different generator protection elements are discussed in greater detail, components of excitation systems are also discussed in detail, this include excitation limiters, governor/ turbine, power system stabilizers and basic review on coordination between limiters and protection.

Chapter three reviews different literatures on protection and excitation control. It further indicates how different authors have conducted studies related to this thesis. A substantial amount of studies have been conducted on protection of generators and control that involve but not limited to generator AVR coordination with generator protection.

Chapter four is a review of the system under study. Real-time simulation model is developed in the RSCAD simulation package which works hand in hand with real time digital simulator (RTDS). The purpose is to study the behaviour of the system under different abnormal conditions in simulation as well as verification using hardware-in-loop testing with a commercial multifunction generator relay.

Chapter five entails the theory of operation and settings, software simulation results and analysis for the particular generator protective functions studied in this dissertation as well as their coordination with respective excitation limiters. Case studies conducted on excitation limiter functioning when coordinated with respective protection elements are also entailed.

Chapter six entails the hardware in-loop testing of generator protection using SEL-300G multifunction generator relay. The results presented are carried out on RTDS. The fundamental purpose of the HIL tests carried out is to verify some of the theories on generator protection, relay settings, and to compare the functioning of the generator software relay with a commercial relay.

Chapter seven summarizes the conclusion based on the work conducted in each chapter and analysis. Recommendations for future work are also entailed.

2. CHAPTER 2- Theoretical Aspects of Generator Protection and Control

2.1. Introduction

Power system protection is an important branch in the field of electrical engineering. A properly designed protection system must be able to clear faults as reliably as possible when there is a disturbance on the protected equipment, and must be able to remain inactive if the protected equipment is in a healthy/stable operating state, or if the fault is not within the protection zone. The theoretical aspects of generator protection elements and excitation controls are presented in this chapter. Background knowledge on generator relay technologies and coordination between generator excitation controls with generator protection is also presented.

2.2. Generator protection

Protection of generators is necessary because they can be subjected to different types of disturbances. These include but not limited to mechanical forces on various parts, electrical disturbances and temperatures rises [9]. Irrespective of how the machine is used, it is always subject to overloading conditions due to that sometimes the machine has to withstand certain overloads and therefore, preventive measures are taken to ensure safety and increased the life span. [10].

Irrespective of efficient design, construction, operation, and protection, faults occurring within the machine cannot be eliminated completely. However, generator protection relays are there to ensure that faults are eliminated within a short space of time. Since generators can be subjected o both internal and external faults, it is advisable that faults occurring from outside be cleared as efficiently as possible before creating permanent damage in the generator and other surrounding power system equipment [10]. To achieve the selectivity and sensitivity of the protection relays, great care is taken for proper coordination. When designing protection systems, abnormal operating conditions and type faults occurring within the machine should be taken into consideration. Protection system design also depends on the size and value of the generating unit [11].

There are many different types of faults that synchronous generators may experience and, therefore, many different types of protection. Some internal faults or abnormal conditions may include [3]:

1. **Internal faults**
   - Stator ground faults and associated areas
   - Rotor ground faults
2. **System disturbances and operational hazards**
   - Loss of excitation (40)
   - Thermal overload (49)

- Off-frequency operation
- backup distance (21)
- voltage controlled time overcurrent (50V)
- Loss of prime-mover (32)
- Generator breaker failure
- Over excitation (24)
- Inadvertent energisation: non-
- synchronized connection (67)
- Unbalanced currents (46)
- Overvoltage (59) and undervoltage (27)
- Loss of synchronism
- Sub synchronous oscillations

Each one of the above listed faults affect the generator uniquely, hence the protection devices has each and every element characteristic. The focus in this thesis is on the coordination of excitation control and protection of the generator, looking into over voltage, over excitation, under voltage and loss of field excitation protection.

2.2.1. Over excitation/ over-fluxing (24)

Overexcitation protection is applied for unit transformers and generators against high flux values resulting in saturation of the iron cores and high magnetizing currents. Both these power system equipment may not be subjected to overvoltage except for transient excursions. Small overvoltage results in higher currents in transformers and excessive flux densities in generators [11].

Overexcitation protection is applied near the generator since the voltage profile is pure sinusoidal, without distortion. High flux values causes saturation of the iron core and during this state, the magnetizing current is high and distorted which increases RMS current value as well as the odd harmonic components. This increase generates high dynamic forces whereas the high RMS value results in overheating [1]. As the flux leaves the iron core during saturation, eddy currents are generated causing current flow in parts that are not designed for the flow of current, this cause over heating again in parts that cannot withstand such condition. In cases where the generator is not connected to the network and the frequency is not kept at a constant value, overexcitation conditions will decrease the system rated frequency which will increase the flux and therefore, overexcitation protection is designed to prevent the long-term overexcited state [12]. The speed of the generator deviates during start-up or shut down.

As per the emf equation (1);

$$E = 4.44 f \emptyset N \tag{1}$$

Over fluxing occurs when the V/f ratio exceeds its nominal value [13]. When the ratio of the voltage to frequency exceeds 105% for a generator, severe overheating can occur. Over excitation on generators can be due to overvoltage or under frequency [2].

2.2.2. Over voltage (59)

Relays are commonly used as means of protection against over voltages. However, transient overvoltage conditions may employ surge arrestors as protection means. Generally, over voltage conditions may be due to transient surges [4]. With health AVR systems, it is very rare for a machine to experience overvoltages. However, there are other factors which may lead to such conditions, these include [12]:

- Operation under manual control with the voltage regulator out of service.
- Defective operation of the AVR in isolated machine operation.
- Sudden loss of load

Sudden load loss should result in transient overvoltage which is handled by AVR and governor. At little or no load supply, some voltage regulators may trip to manual causing a substantial increase in the machine terminal voltage [1]. If an overvoltage sensitive load remains connected, loss of revenue consequences may be severe. Isolated or weak interconnected networks can also be subjected to prolonged overvoltage conditions due to the faults [8]. It is therefore important to provide overvoltage protection with either inverse definite minimum time (IDMT) or definite time with a time delay long enough to prevent operation during normal regulator action.

The relay protection element against overvoltages should trip both the main circuit breaker and the excitation [12] because high voltages may cause excessive dielectric stress on the generator insulating materials thus causing insulation failure. Hence sometimes overvoltage protection is provided to act against high dielectric stress [2].

2.2.3. Under voltage (27)

Undervoltage protection is sometimes used as a backup for other protection functions where each fault results to an undervoltage condition [7]. A typical example of these protective functions is the field excitation failure, which is why these two are sometimes coordinated with underexcitation limiters. Undervoltage conditions from transmission systems occurring due to insufficient reactive power generation should not trip the generation side [8]. For cases where the generator is supplying an isolated power system, undervoltage protection relay is required. This is because in isolated systems AVR failure or overloading conditions are most likely to occur. Where undervoltage protection element is applied an undervoltage pickup level and a time delay are required [10][12].

Although in some cases undervoltage condition does not directly affect the generator, overheating due to prolonged operation at low voltages damages the auxiliary motors. To mitigate such conditions, under voltage relays may be applied to trip the generator and protect the motors. Settings must be applied to avoid incorrect operation during voltage dips associated with motor starting [10][12][14].

Stability issues normally are due to operating generators below the minimum voltage of 95%. This could also result in a condition where the machine draws excessive power from the grid and improper operation of voltage sensitive devices. It is therefore important to operate generators continuously at a minimum voltage of 95% of its rated voltage at rated power and frequency. It is a common practice to alarm on under voltage condition and not trip the generator. Generator under voltage alarm operation may be detected to alert the operators to can take appropriate actions [15].

2.2.4. Field failure (40)

Field excitation failure on a machine can be due to a short in the field leads, flashover of the exciter commutator, operator error or accidental tripping of the field breakers [2]. During field excitation failure, the synchronous generator starts functioning like an induction generator. The rotor speed increases, active power output decreases, and the generator draws reactive power from system. High currents are induced in the rotor and stator current as high as 2.0 per unit is possible [16]. These high currents cause dangerous overheating in a very short time. A two-element offset mho relay is used to protect generators against field failure conditions. When this relay is set properly, it is able to detect excitation failure conditions from full to almost no load. The MHO is applicable to any type and size of generators [2].

The most widely applied method for detecting a generator loss of field condition on major generators is the use of distance relays to sense the variation of impedance as viewed from the generator terminals [13]. A two-zone (figure 2-1) distance relay approach is widely used within the industry to provide high-speed detection. An impedance circle diameter equal to the generator synchronous reactance and offset downward by ½ of the generator transient reactance is used for the Zone 2 distance element. The operation of this element is delayed approximately 30-45 cycles to prevent misoperation during a stable transient swing. A second relay zone, set at an impedance diameter of 1.0 per unit (on the generator base), with the same offset of ½ of the generator transient reactance is used also. This Zone 1 element has a few cycles of delay and more quickly detects severe underexcitation conditions. When synchronous reactance is less than or equal to 1.0 per unit (e.g. hydro generators) only the Zone 2 is used and is set with the diameter equal to 1.0 per unit [5].

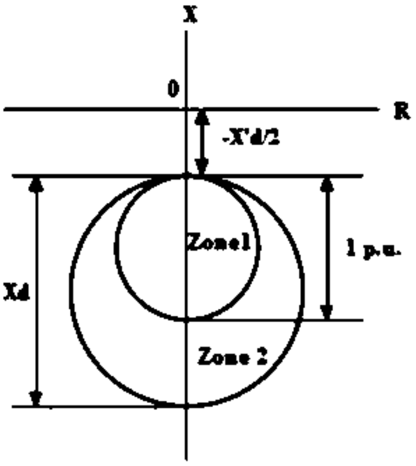

Figure 2-1: Loss of field R-X diagram [5]

2.3. Excitation systems

Synchronous generator excitation system is key part of the power system. The excitation system of a synchronous generator makes it possible to supply the energy generated by an engine (turbine) to the power grid. As a result, high priority is assigned to the reliability and availability of excitation equipment when choosing systems [13]. Generators require excitation systems to remain synchronized. The basic function of excitation systems is therefore to provide the energy required for the magnetic field keeping the generator in synchronism. They also affect the amount of reactive power delivered or absorbed [9][17]. Constant power factor regulation, AVR and constant reactive power regulation are some control functions that may be applied to excitation systems. A typical excitation control system block diagram is shown in figure 2-2 [13].

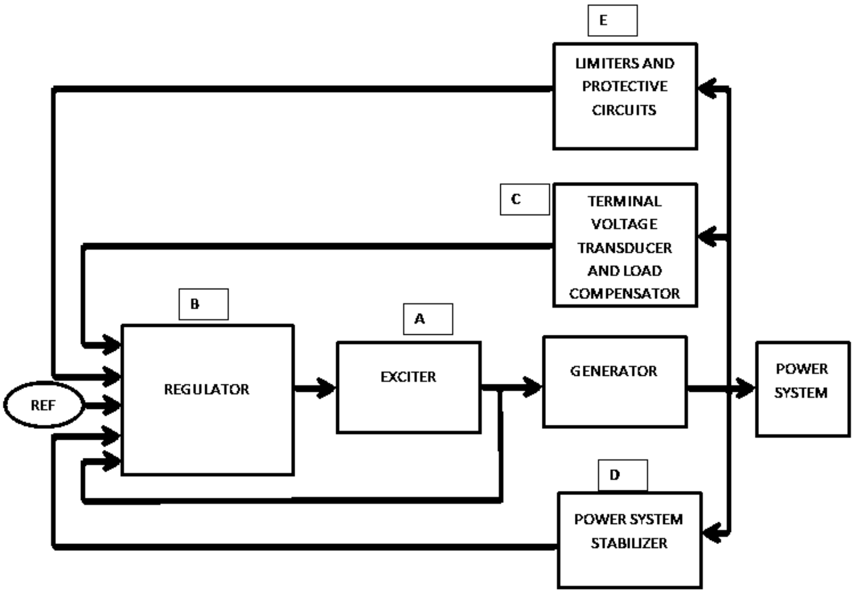

Figure 2-2: Synchronous generator excitation control system block diagram [13]

(A) Exciter- An exciter provides the synchronous machine field winding with power

(B) Regulator- Processes and amplifies input control signals to a level appropriate for control of the exciter.

(C) Terminal voltage transducer and load compensator- Senses generator terminal voltage, rectifies and filters it to dc quantity, and compares it with a reference (REF) which represents the desired terminal voltage.

(D) Power system stabilizer- Provides an additional input signal to the regulator to damp power system oscillations.

(E) Limiters and protective circuits- Include a wide array of control and protective functions which ensure that the capability limits of the exciter and synchronous generator are not exceeded.

The excitation system may be configured with manual or automatic control. Automatic controls may have supplementary controls ensuring that the generator operates within its capability. Supplementary controls may be [18]:

- Excitation level limits
- Stator current limit
- Power system stabilizers
- Reactive power controls

The system voltage in AVR operation mode is kept within acceptable levels by controlling the reactive power in the system [13].

2.3.1. Types of excitation systems

Depending on the excitation power source utilised, excitation systems can be classified into the following categories:

2.3.1.1. AC excitation systems

Alternators are used as sources of generator excitation power in excitation systems. To produce DC current for the field windings, alternating current output from the exciter is rectified through non-controlled or controlled rectifiers. Rectifiers can be classified as rotating or stationary. Some excitation systems in the early years used a combination of rotating and magnetic amplifiers for regulation [13] but new systems electronic amplifier regulators are used. Depending on the method of output control, source of excitation and rectifier arrangement, AC excitation systems can thus take many forms [13].

2.3.1.2. DC excitation systems

These excitation systems employ direct current generators as their source through slip rings. Exciter may be separately or self-excited driven by a motor or shaft of the generator.

When DC excitation systems are separately excited, the pilot exciter supplies the exciter field winding. DC excitation systems represent early systems, spanning the years from the 1920s to the 1960s. They lost favour in the mid-1960s and were replaced by ac exciters [13][17].

The voltage regulators for such systems range all the way from the early non-continuously acting rheostatic type to the later systems utilizing many stages of magnetic amplifiers and rotating amplifiers [13]. DC excitation systems are gradually disappearing, as many older systems are being replaced by ac or static type systems. In some cases, the voltage regulators alone have been replaced by modern solid-state electronic regulators [13][17].

2.3.1.3. Static excitation systems

All components of these excitation systems are stationary. Filed current is supplied directly to the field winding via slip rings. Main generator supplies power through a step down transformer to the rectifiers. This transformer steps down the voltage to acceptable level [13]. Static excitation systems maybe classified into;

- Compound-controlled rectifier systems
- Potential-source controlled-rectifier systems
- Compound-source rectifier systems

2.4. Excitation limiters

Excitation limiters play a vital role in limiting generator parameters within allowable capabilities. These limiters include [5][13][17]:

- Over excitation/ Maximum excitation limiters (OEL/MXL)
- V/Hz limiters
- Under excitation/ Minimum excitation limiters (UEL/MEL)

2.4.1. Over excitation limiter (OEL)

The purpose of the overexcitation limiter is to protect the generator from overheating due to prolonged field overcurrent. To ensure that full Var capability of the generator is available the limiter settings are coordinated with generator capability in the over excitation region allowing the exciter to respond during field forcing [19][20]. The limiter setting must also allow the short time field current capability usage. The OEL takes over AVR control to limit field current above rated values. A constant field resistance is assumed in simulation studies whereas other parameters like field voltages and currents are taken as a percentage of their rated values. This relationship is plotted in figure 2-3.

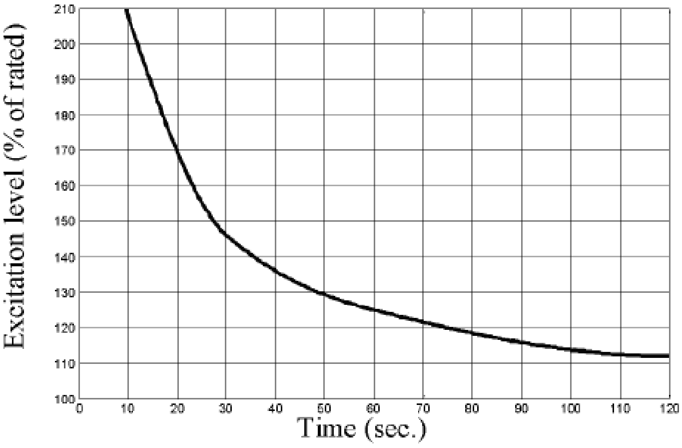

Figure 2-3: Field voltage short time capability [17]

2.4.2. V/Hz limiter

These limiters control the voltage to frequency ratio on generators by controlling flux. Excessive overheating can result due to sustained high values of flux during low frequency or overvoltage conditions. The effect of poor control of overexcitation conditions can affect unit transformers as well. Therefore, V/*Hz* limiting and protection requirements are determined by the transformer limitation. In cases where the generator and transformer voltage ratings are similar, the limitation of the generator becomes restrictive [13][21]. V/Hz limiter has the ability to limit the generator voltage to frequency ratio through generator voltage monitoring. The ±5% steady state operation limit permit short time excursions when there are transient voltage conditions [5][22]. Figure 2-4 illustrates a typical V/Hz curve for a generator plotted against time.

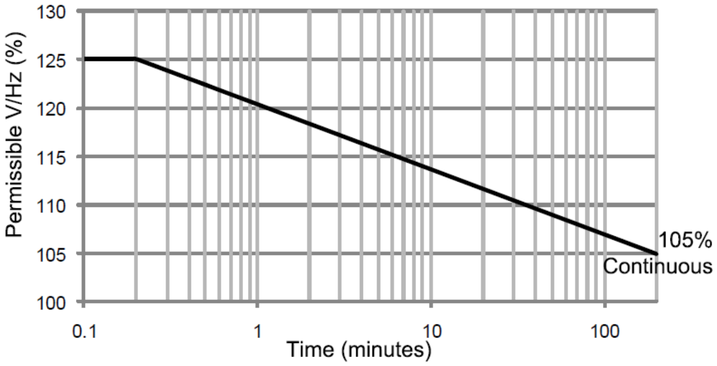

Figure 2-4: Typical V/Hz curve for a generator [21]

2.4.3. Under excitation limiter (UEL)

The UEL is intended to prevent reduction of generator excitation to a level where the small-signal) stability limit or the stator core end-region heating limit is exceeded. The control signal of the UEL is derived from a combination of either voltage and current or reactive and active power. The limits are determined by the signal exceeding a reference level. There are a wide variety of implementations of the UEL function. Some UEL applications act on the voltage error signal of the AVR; when the UEL set limit is reached, nonlinear elements begin to conduct.

In a more widely used form of UEL application, the limiter output signal is fed into a high-value gate which gives control to the larger of the voltage regulator and UEL signals; when the UEL set limit is reached, the limiter is given full control of the excitation system until the limiter signal is below the set limit [5][13].

Additional inputs to AVR summing junction in some applications control the limiter. When not in operation, the UEL output is zero and when conditions change, the limiter output increases proving a boosting signal to the AVR. However, this type of application requires a sufficient UEL gain overcome the bucking effect of the AVR [24][25].

Three different underexcitation limiter models have been developed to accommodate different applications. The limiting characteristics are plotted in real and reactive power axes. The three models are [5][13][24]:

- Multi-segment straight line characteristic
- Circular characteristic
- Straight line characteristic

2.4.3.1. Circular characteristic

The type UELl model has a circular limit boundary when plotted in terms of machine reactive power vs. real power output. Figure 2-5 shows UEL1 model.

The phasor inputs of I_T and V_T are synchronous machine terminal output current and voltage with both magnitude and phase angle of these ac quantities sensed.

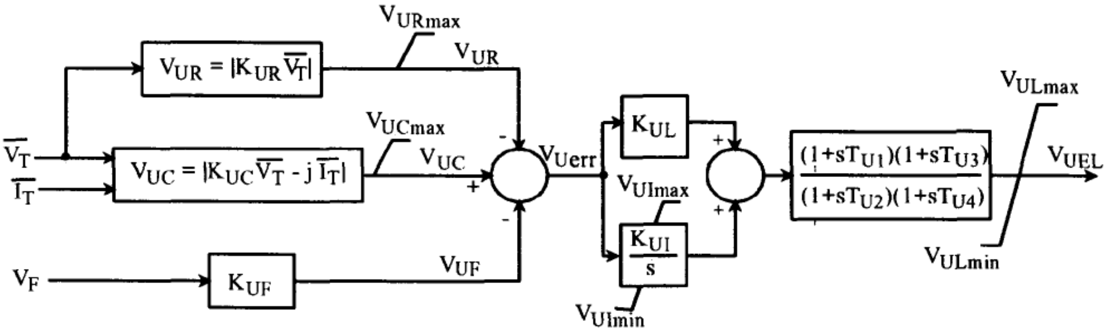

Figure 2-5: Circular characteristic UEL [25].

2.4.3.2. Straight line characteristic

Figure 2-6 shows the straight-line characteristic UEL model with a linear limit boundary. The model is implemented in any of the three conditions [17][19]:

- When $K_1 = 0$, active and reactive power are unaffected by V_T
- When $K_1 = 1$, real and reactive components of machine current I_T are divided by V_T using
- Similarly, when$K_1 = 2$, P_T and Q_T are by V_T [25].

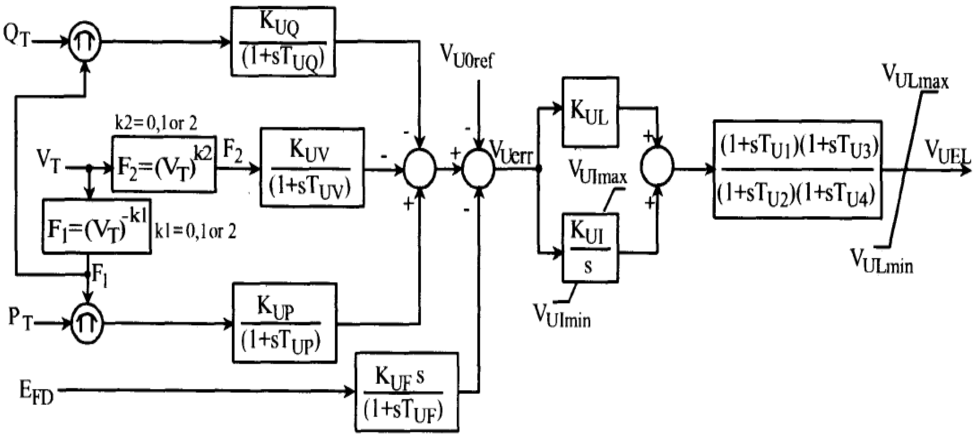

Figure 2-6: Straight-line characteristic UEL [25].

2.4.3.3. Straight line characteristic with multi-segments

UEL shown in figure 2-7 has similarities to the straight-line model. This limiter allows up to four linear segments to make up the limit boundary. This model follows the underexcited region of the capability curve more closely than the normal straight-line model [25][26]. The model is implemented by:

- k= 0 so that $F_1 = F_2 = 1$, leaving the active power input unaffected by terminal voltage.
- When k=l or k=2, active power input is divided by terminal voltage and multiplied by the same factor after establishing the appropriate limit segment.

Based on the value ofV_{PU}, SWI can be used to determine the segment used as the limit at any particular time [25].

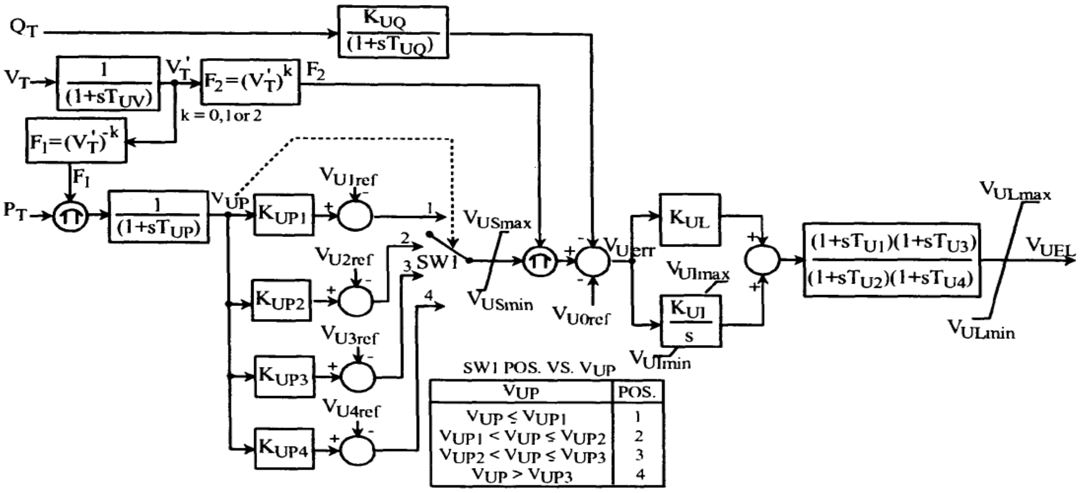

Figure 2-7: Multi-segment straight-line characteristic UEL [25].

The UEL settings should be based on the needed protection, i.e., system instability or stator core heating. In addition, the limiter should be coordinated with generator field failure protection.

2.5. Governor/turbines

In the post disturbance period and to maintain acceptable system performance, turbine governor control may have to become an integral part of the protection system. Maintaining the proper speed regulation and the division of the load for the generating units on the power system are major roles of the turbine governor control. Depending on the control requirements, droop and frequency controls are utilized. Droop (otherwise known as speed or load control) decreases with a linear characteristic behavior. The operation of synchronous machines is locked at the system frequency; therefore the load controller is the droop governor. Governor valves open up to maintain after receiving signals from the governor. This happens after an increase in load and is so that the additional system load is accommodated. One generator is prevented from trying to pick up the extra load by the governor droop control. The load change being shared among different units as well as overall improved system stability are some of the benefits [18][27][28].

2.6. Power system stabilizers

The power system stabilizer uses auxiliary stabilizing signals to control the excitation system so as to improve power system dynamic performance. Commonly used input signals to the power system stabilizer are shaft speed, terminal frequency and power. Power system dynamic performance is improved by the damping of system oscillations. This is a very effective method of enhancing small-signal stability performance [13][18].

2.7. Coordination of generator capability, control and protection

Excitation system controls prevent the system operation outside its generator capability. These controls are discussed based on how they are modelled, how they are applied with AVR as well as how the operate to control system parameters. The excitation limiter operation mainly depends on the system needs. OEL acts against the supply of excitation current more than what the system can withstand whereas the UEL acts to boost the system reduced excitation levels [23][29]. Protection functions in both under and over excitation regions are applied in conjunction with the excitation limiters. This is called coordination. It is mainly achieved through correspondence in magnitude and time delay settings between limiters and protection functions [5][29][30].

3. CHAPTER 3- Literature Review

3.1. Introduction

This chapter entails a review of literatures related to coordination of generator protection and control. A substantial amount of studies have been conducted on protection of generators and control that involve but not limited to generator AVR coordination with generator protection. There are a variety of methods and techniques used in literatures to achieve proper coordination of generator protection with generator control and load capability that are available in literatures [5][13][31]. Furthermore, there is always a need to improve the existing coordination to prevent any misoperation of generator protection during disturbances.

Every generator system is subjected to disturbances primarily due to faults occurring internally or externally. Turbine governor controls and generator excitation aid the system to adapt to new steady-state conditions. This occurs in the event of a disturbance. The coordination of relays is of great importance, so that they provide protection efficiently during disturbances such as thermal and stability limits. In literatures, these limits are mostly defined in the active-reactive power plane (P-Q plane) that consequently implies that the operation of a generator should always be within the limits [31][32]. This condition is usually met by the limiters embedded in the voltage regulator. This chapter reviews protection principles between a synchronous generator AVR, its associated limiters and protective functions [33].

3.2. Excitation control

Authors in [35] investigated the excitation system models of synchronous generator and indicated that excitation current is provided by excitation system and usually consists of AVR, exciter, measuring elements, power system stabilizer, limiting and protective unit. The same is indicated in [13]. Additionally, [13] and [9] considers well-functioning excitation system as the one with a capability to supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage as the output varies within the continuous capability of the generator, this is similarly implied in [5] where it is indicated that an excitation system operating in AVR mode maintains system voltage by controlling reactive power and increasing synchronizing torque when required. However, most recent literatures focus more on the AVR mode of operation in an excitation system excitation whereas [5][13][31] included that there are excitation systems which operate with no automatic regulation but mostly AVR mode is used. From the literatures reviewed, excitation systems have been classified into three broad categories based on the excitation power source used [13][17][18][35], i.e.:

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

Despite the three categories, [17][18] and [13] have indicated that AC excitation systems are widely used compared to DC and static excitation systems. Authors in [13] describe DC excitation systems as the type that utilize dc generators as source of excitation power and provide current to the rotor of the synchronous machine through slip rings. Moreover, AC excitation systems also referred to as alternators in [13] and [17] are said to be utilized as power sources to the main generator. Static excitation systems consist of stationary components. However, in [35] although the three major categories of generator excitation systems are defined, DC type exciters alone are said to be mainly suppressed by other two types and a few new synchronous machines are being equipped with these.

3.3. Generator Capability

Authors in [36] investigated the impact of synchronous generators excitation supply on protection and relays. Synchronous generators have been described to have two types of operational limits i.e. thermal and stability limits, this is similar to [5]. In [9] and [5] the thermal limits have been sub-categorized into armature current limit, field current limit and the stator end core limit. The generator capability curve shown in figure 3-1 indicates how the limits are plotted in a P-Q diagram.

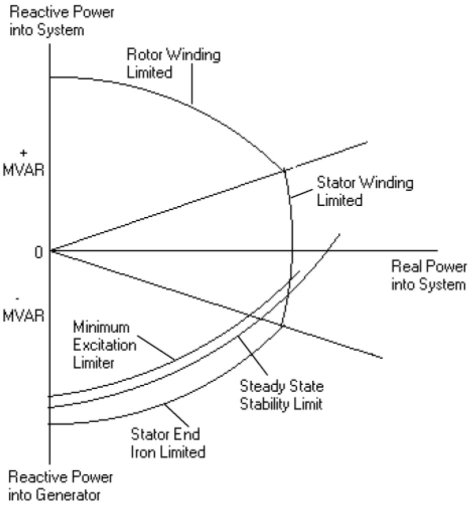

Figure 3-1: Capability curve of a generator [5]

Authors in [5] indicated that steady operating limits are provided at generator rated voltage. Steady-state stability limit is a consequence of the power transfer equation between a generator and the network that it is supplying. In most literatures reviewed, generator capability is said to include supplementary controls [5][36]:

3.4. Overexcitation operation

Excitation systems as discussed in literatures have controls and limiters designed to protect generators against thermal damages. Over-excitation limiter and V/Hz limiter are typical control limiters designed to operate in the overexcited region [37].

3.4.1. Overexcitation limiter (OEL)

The limiter is also called a field current limiter or maximum excitation limiter in [17][18]. According to [5], the function of an OEL is to protect the generator field circuitry from excessive current versus time heating whereas in [36] the purpose of the limiter is to essentially limit the field current value so that the generator operating point does not go above the field current limit. There is no evident argument between the literatures in terms of the purpose of overexcitation limiters embedded on AVR systems, most importantly the literatures could rather indicate or focus more on the purpose of coordinating the limiter with protection. However, [5] included that OEL setting should be coordinated with the generator capability in the overexcitation region and should also allow the exciter to respond to fault conditions where field current is boosted to a high level for a short period of time. Authors in [5] argue that the overexcitation limit of synchronous generator plays an important role in the voltage stability of power systems. Achieving maximum use of the overexcitation capability requires adequate coordination between generator control and protection. The paper provides an example of coordination between overexcitation limiter (OEL), field overcurrent protection and automatic voltage regulator (AVR) for a synchronous generator. The coordination achieved is then verified by a model simulation using an electromagnetic transient program for practical scenarios of interest. From most literatures reviewed, excitation limiters built are different but the operation is the same i.e. overexcitation condition detection, defined time-overload period, and then reduction of the excitation to safe levels. Most importantly, [17] included the importance limiting action provided by OELs to prevent overheating due to high field current levels while allowing maximum field forcing.

A simple OEL model will have a fixed time delay and pickup point and will instantly reduces the excitation set point to acceptable levels. A combination of instantaneous and inverse-time pickup characteristics is found in common OEL types [17]. In the studies conducted in this thesis a simplest form of OEL is modelled with a fixed time delay for simplicity. In [13] a simplest OEL model is presented with a high setting that provides almost instantaneous limiting at 1.6 times full-load current (FLC) and a low setting of 1.05 times FLC in conjunction with a ramp timing function which provides a limiting action with time delay dependent on the level of field current, the same limiter is presented in [17][18].

3.4.2. V/Hz limiter

V/Hz limiter is commonly used to limit the generator V/Hz ratio by limiting the generator voltage to a programmed setting. Most literatures considers field current limiters under overexcitation operating mode, however [13] and [17] discuss the V/Hz limiter as well. The operation of V/Hz limiter in comparison to OEL is similar. When per unit V/Hz ratio exceeds the limiting value; a strong negative signal drives the excitation down. In case the limiter fails to operate, V/Hz protection serves as backup. The limiter typical settings discussed in [13] are 1.07 to 1.09 pu to control the V/Hz ratio.

3.5. Under excitation operation

Most literatures reviewed states that excitation systems rarely operate at the extremes of their capabilities until a point where the system voltage starts rising or falling outside its normal operating limit therefore, this permits short term operation of a generator system beyond its steady state limit. The mechanism of operation involves comparing the actual point of operation to the desired limit, after then the regulator determines when/ whether it is appropriate to adjust the generator field current in order to remain within the desired operating conditions.

3.5.1. Under excitation limiter (UEL)

UEL models utilized in large power system stability studies are presented in [24] and [17]. These models are compatible with recommended excitation system models. With these models, most under excitation limiters in use on large power system-connected synchronous machines can be represented. Two UEL models have been developed with the second type as a combination of single and multi-segment straight-line characteristics. Most literature show that circular characteristic type UEL1 is closely coordinated with loss of field excitation because of its circular nature which allows easier mapping from P-Q to R-X diagram. Typically, UEL uses voltage and current or real and reactive power as inputs to the model with the limiter output applied to AVR either by adding it to the summing junction of the voltage regulator or to the HV gate so as to override the normal action of a regulator. In [17] and many other literatures, it is indicated that the action of the UEL depends on the implementation function. The action of the UEL can sometimes take the PSS out of service and/or cause interactions, which may not normally occur during normal operation when the UEL characteristic is not reached.

Authors in [38] present a method for parameter estimation when modelling an under-excitation limiter. The characteristic had been obtained during a start-up test of a generation unit. The model presented was inspired by a model proposed by the IEEE task force on excitation [38][17]. However, this method to estimate the limiter parameters is complex in a sense that it requires start-up generator data or manufacturer data with is not included in the literature to validate simulation results based on straight-line characteristic; it can however still be utilized and adjusted based on each generator steady state operation. Moreover, [39] argue that the action of excitation system protective limiters and reactive power regulation are often not taken into account in planning studies, and actual units may be quite different than simulations.

This is true since it may lead to incorrect predictions of actual stability limitations, or even voltage collapse phenomena. Irrespective of different modelling of the limiters, the operation of these limiters remains the same. It has been seen and can be concluded that there’s quite a number of similarities in most excitation control and protection of generator implementations. However, some of the methods mainly depend on the user especially during simulation studies.

The thesis focuses more on the overexcitation and underexcitation limiter operation and coordination with different generator protective functions. Over excitation operation of the generator is closely coordinated with over excitation and/ over voltage protection whereas underexcitation operation is coordinated mainly with loss of field protection but not limited to it. Under excitation limiter types require special attention in terms of choosing which model type is best suited for the type of coordination study done.

4. CHAPTER 4- Methodology

4.1. Introduction

This chapter discusses the system studied and utilized for simulation case studies conducted in this thesis. Real-time simulation model is developed in the RSCAD simulation package which works hand in hand with RTDS. The purpose is to study the behaviour of the system under different abnormal conditions in simulation as well as verification using hardware-in-loop testing (HIL) with SEL 300G commercial multifunction generator relay as this approach enables generator protection studies to be carried out in a more real testing environment. Additionally, the hardware generator protection relay can interact with the simulated power system network. Furthermore; this chapter entails an overview of the hardware generator protection relay which involves closed-loop connections between RTDS. Figure 4-1 illustrates a block diagram of the methodological approach followed during the studies conducted in the dissertation.

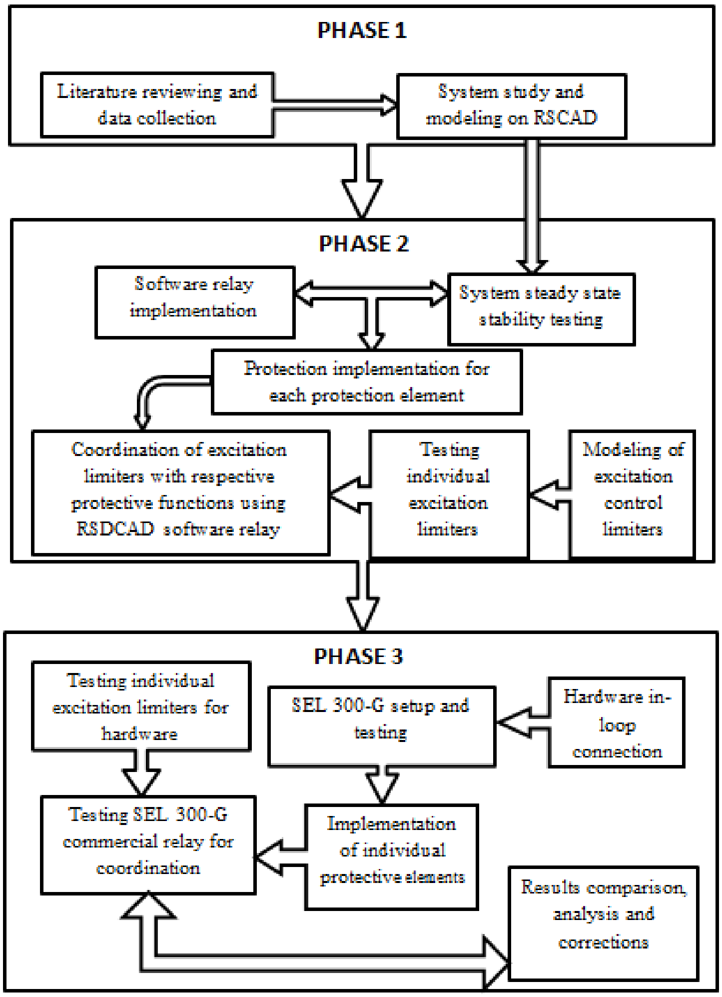

Figure 4-1: Methodology block diagram

4.2. Real time digital simulator

A simulation is the prediction of the behaviour of a specific system. It uses mathematical models of the system to predict its behaviour. A real time simulation takes the same amount of time to indicate a response of a system as the actual system would take. RTDS is a different power system simulator in a sense that its principle of operation is not just to execute the simulation in real time but also to allow physical equipment under study to be connected, allowing testing of protection relays and system controllers to be carried out easily. Based on how the technology has progressed to microprocessor-based relays, modern protection relays are highly complex systems and it is very difficult to represent the detailed characteristics of an individual manufacturer's relays in a power system simulation by means of mathematical models [40]. This is one of the reasons why the real-time simulator is a better option for protection engineers since it can be used for hardware-in-loop testing of actual protection relays and system controllers. The equipment connected to the real-time simulator for testing can interact with the power system simulation in real time. The hardware-in-loop testing can be used for the verification of the equipment performance under different system operating conditions and contingencies.

RSCAD is the software for the real-time simulator which comprises a group of sub-programs that are used to build, program, compile, run and control the real-time simulator. It is the interface between the user and the simulator. Over the years, the environment of RSCAD has been improved due to collaboration between the manufacturer of the simulator and some well-known companies in the field of electrical engineering [41], [42], [43]. The software package consists of different pre-developed generic models of protection relays for real-time simulation studies [44]. Protection studies carried out in this thesis has utilized such generic relay models that are highly detailed and possess all the principal functional elements typically found in actual protection relay hardware.

4.3. System under study

The system modelled on RTDS is a well-known power system network adapted from [13]. The system has been selected based on being a popular and ideal model to carry out power system stability and control studies, as well as the advantage of having readily documented parameters for both the generator and its controls since it is important to have detailed and practical information of a system before modelling. The system model is illustrated in figure 4-2 as a single-line diagram where capacity of the generating plant is 555 MVA with a terminal voltage of 24 kV which is stepped up to 400 kV for connection to the HV bus feeding two transmission lines. The two transmission lines are connected to a remote system which is represented as an infinite bus.

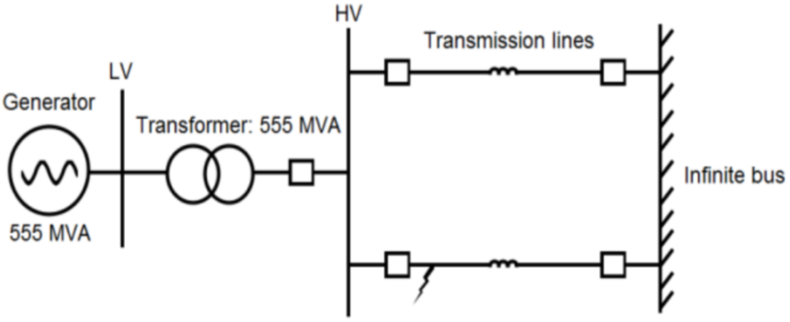

Figure 4-2: System under study

The generator model uses power system circuits as a form of excitation system. An exciter is modelled separately and takes in the control of excitation voltage coming from the AVR controller. This enables the study of field excitation related studies to be performed.

4.4. Phase domain synchronous machine modeling

The phase-domain synchronous machine model allows the adjacent excitation system to be modelled solely as an electrical circuit which forms part of the electromagnetic transient solution. This is advantageous in a sense that the electrical equipment supplying the generator field circuit can now be represented in detail using power system components which enables modelling and testing of more realistic contingencies.

Figure 4-3 illustrates the two phase domain machine excitation system configurations. In this thesis, a separate exciter is modelled using power system circuits which enables excitation system studies related to generator protection. Inside the PDSM where parameters are input, there is an option to choose a field excitation type. This option determines the type of field excitation which the user intends to use. If the "Power System Node" is selected, then the component will have the view as illustrated in figure 4-3 in the draft canvas. In this case, two power system nodes will appear (F+ and F−) which can be used to energize the field winding using actual power system components (e.g. DC source model or power electronics).

If this option selected, the user has to provide the field current (kA) required for 1 pu unsaturated open−circuit terminal voltage at rated speed. This value is entered in the dq−based machine configuration menu. After compiling the circuit, the required field voltage for 1 pu unsaturated open−circuit terminal voltage at rated speed, and the required field voltage for initialization of the machine will be written in the MAP file [27]. Furthermore, the machine model uses excitation control, governor/turbine control as well as the power system stabilizer which is employed for generator stability.

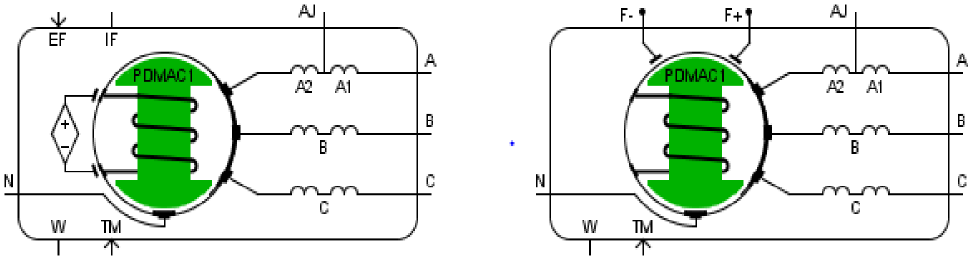

Figure 4-3: Synchronous generator model for internal faults [27]

The phase domain synchronous machine (PDSM) model is available for simulating stator−ground and internal faults. The neutral of the machine (N) and a point of fault in phase A (AJ) are available for connection to other power system components. To be able to simulate synchronous machine internal faults, the self and mutual inductances of machine windings including faulted windings must be computed as functions of rotor position and saturation. If the dq−based method is used for computing synchronous machine inductances, the model can operate differential and neutral overvoltage protection schemes [27]. The PDSM model presents fixed-reference frame for stator windings and d-q representation for the rotor winding [4]. The voltage equations utilized for machine modelling are [45];

$$v_{abcs} = R_s i_{abcs} + s\lambda_{abcs} \qquad (2)$$

$$v_{qdr} = R_r i_{qdr} + s\lambda_{qdr} \qquad (3)$$

s -subscript of stator windings

r- Subscript of rotor elements.

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda'_{qdr} \end{bmatrix} = \begin{bmatrix} L_s(\theta_r) & L'_{sr}(\theta_r) \\ \frac{2}{3}(L'_{sr}(\theta_r))^T & L'_r \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i'_{qdr} \end{bmatrix} \qquad (4)$$

(4) Shows the flux linkage equation, prime terms in (4) illustrate rotor terms referred to the stator. The stator inductance matrix (5) is deduced from a non-uniform air-gap approximation. From the flux linkage equation, the rotor and stator rotor inductances are illustrated by equation (6) and (7).

$$L_s = \begin{bmatrix} L_{is} + L_A - L_B\cos(A) & -L_A/2 - L_B\cos(B) & -L_A/2 - L_B\cos(C) \\ -L_A/2 - L_B\cos(B) & L_{is} + L_A - L_B\cos(C) & -L_A/2 - L_B\cos(A) \\ -L_A/2 - L_B\cos(C) & -L_A/2 - L_B\cos(A) & L_{is} + L_A - L_B\cos(B) \end{bmatrix} \qquad (5)$$

$$L'_{sr} = \begin{bmatrix} L_{mq}\cos(\theta_r) & \cdots & L_{md}\sin(\theta_r) & \ldots \\ L_{mq}\cos(\theta_r - 2\pi/3) & \cdots & L_{md}\sin(\theta_r - 2\pi/3) & \cdots \\ L_{mq}\cos(\theta_r + 2\pi/3) & \cdots & L_{md}\sin(\theta_r + 2\pi/3) & \cdots \end{bmatrix} \qquad (6)$$

$$L'_r = \begin{bmatrix} L'_{lkq1} + L_{mq} & L_{mq} & 0 & 0 \\ L_{mq} & L'_{lkq2} + L_{mq} & 0 & 0 \\ 0 & 0 & L'_{lfd} + L_{md} & L_{md} \\ 0 & 0 & L_{md} & L'_{lkd} + L_{md} \end{bmatrix} \qquad (7)$$

4.4.1. Function of windings and construction.

To establish mutual and self-inductances for the PDSM model, stator winding function represent the stator winding. Machine characteristics are utilised to construct winding functions. These characteristics include [45][52][53];

- Stator slots
- Conductors per slots
- Specific coils occupying sequence of slots
- Number of poles

After establishing the winding functions, mutual and self-inductances are computed using equation (8)(9) and (10) [45]. Equation (11) is deduced because winding functions are a function of $\emptyset$ alone.

$$L_{yx} = L_{xy} = K_0 A_{xy} - K_2 B_{xy} \qquad (8)$$

$$A_{xy} = \langle n_x n_y \rangle - \langle n_x \rangle \langle n_y \rangle \qquad (9)$$

$$B_{xy} = \langle n_x n_y \cos(2p(\emptyset - \theta_r)) \rangle - \langle n_x \rangle \langle n_y \cos(2p(\emptyset - \theta_r)) \rangle - \langle n_y \rangle \langle n_x \cos(2p(\emptyset - \theta_r)) \rangle \qquad (10)$$

$$L_{yx}(\theta_r) = L_{xy}(\theta_r) = L_{xy0} + L_{xy1}\cos(2p\theta_r) + L_{xy2}\sin(2p\theta_r) \qquad (11)$$

Geometric coefficients in equation (12) and (13) are calculated from the simplified form equation (11), the stator inductances are then computed using (14) and (15).

$$K_0 = \frac{(L_{md}+L_{mq})}{2(L_{AA0}-L_{AB0})} \qquad K_2 = \frac{(L_{md}-L_{mq})}{\sqrt{{L_{AA1}}^2+{L_{AA2}}^2} + 2\sqrt{{L_{AB1}}^2+{L_{AB2}}^2}} \qquad (12)$$

$$K_{r1} = -\frac{L_{md}}{\int_0^{2\pi} n_A \cos(p\emptyset)\, d\emptyset} \qquad K_{r2} = \frac{L_{mq}}{\int_0^{2\pi} n_A \cos(p\emptyset)\, d\emptyset} \qquad (13)$$

$$L'_{xfd} = L'_{xkd} = K_{r1} \langle n_x \sin(p(\emptyset - \theta)) \rangle \qquad (14)$$

$$L'_{xkq1} = L'_{xkq2} = K_{r2} \langle n_x \cos(p(\emptyset - \theta)) \rangle \qquad (15)$$

4.4.2. Internal Faults

Internal faults are basically the asymmetry winding distribution of the machine therefore, winding theory is required. Faulty windings in the model are treated as a bunch of normal windings with fewer coils connected to another phase winding or to ground. Additional equations are substituted inserted in (4) to obtain mutual and self-inductances for sub windings [45]. In real time implementation, the impedance fault matrix in (16) is additional with (17) and (18) as voltage and current vectors respectively. This is for an N parallel connection of a round rotor machine with a fault in winding A2.

$$v(t) = \left(R + R_g + R_f\right)i(t) + s\left(L(t) + L_g + L_f\right)i(t) \tag{16}$$

$$v = \left[v_{A1}v_{Af1}v_{Af2}\cdots v_{AN} \quad v_{B1}\cdots v_{BN} \quad v_{C1}\cdots v_{CN} \quad v_{fd}' \quad 0 \quad 0 \quad 0\right] \tag{17}$$

$$i = \left[i_{A1}i_{Af1}i_{Af2}\cdots i_{AN} \quad i_{B1}\cdots i_{BN} \quad i_{C1}\cdots i_{CN} \quad i_{fd}' \quad i_{kd}' \quad i_{kq1}' \quad i_{kq2}'\right] \tag{18}$$

f and g subscripts are for fault and ground elements respectively.

R is a diagonal winding resistances matrix.

L is the rotor position.

Recurrent equation (19) is obtained by rearranging the terms [45]. Where variables with *n* refer to current time step and *n-1* is the previous time step.

$$i_n = \left(X_n + \frac{\omega_b t_s}{2} R_r\right)^{-1} \left[\left(X_{n-1} - \frac{\omega_b t_s}{2} R_r\right) i_{n-1} + \frac{\omega_b t_s}{2}\left(v_n + v_{n-1}\right)\right] \tag{19}$$

Where,

ω_b Nominal angular speed,

R_t Total resistance matrix, and

t_s Time step length

4.5. Software generator relay

The multi–function generator relay available at RSCAD library is suitable for providing the protection function on synchronous machines. Differential elements for phase and neutral currents, 100% stator protection, loss of field protection, out–of–step, volts per hertz, and other additional relay elements provide comprehensive protection for the generator. The phase voltages and currents and neutral voltage and current are connected to inputs of the generator function. The relay also has the facility enabling the user to identify the generator protection element which has operated at a particular instant.

4.6. Hardware relay

A SEL-300G multifunction generator relay is used in this thesis for hardware in-loop testing. The main reason is to verify the results obtained during software relay simulations.

4.6.1. SEL-300G relay

The SEL-300G relay is a multifunctional digital microprocessor based used to protect the large generators found in power stations. This relay contains different protective functions that are implemented to protect the generator from various types of fault and system contingencies. The relay offers a variety of protection functions (figure 4-4) including but not limited to over voltage (59), undervoltage (27), loss of field excitation (40), overexcitation (24).

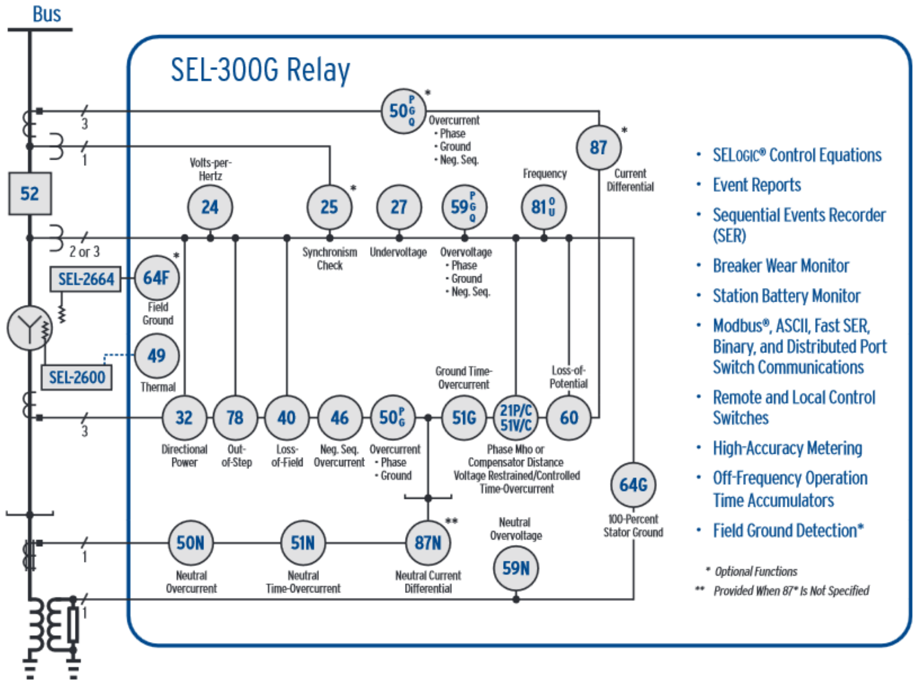

Figure 4-4: SEL 300-G protection relay functions [12]

For purpose of configuring and setting the relay for each protection element tested, AcSELerator QuickSet software is used. It is an easy-to-use yet powerful tool with template design capabilities for easy, consistent settings and applications to help a user get the most out of the SEL device. The user can activate or deactivate any protection elements provided by the SEL 300G relay according to the requirements of the designed protection system. However, loss-of-potential (60) protection cannot be deactivated since it’s there to detect any loss of signal from the voltage transformers used to measure generator terminal voltages. The loss-of-potential element triggers an alarm which notifies the system operators in an emergency situation. It is also used to stop the relay from tripping during loss of transformer voltage signal.

4.6.2. HIL connection of the generator protection relays

Figure 4-5 shows the hardware in-loop connection employed for hardware testing with SEL 300G.

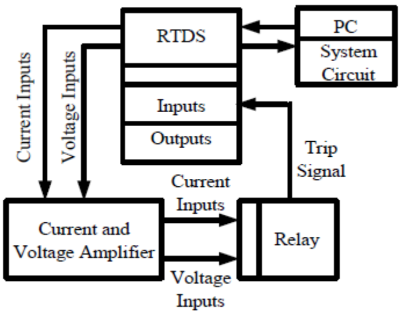

Figure 4-5: Schematic representation of HIL

The relay receives current and voltage signals from the secondary side of instrument transformers of the system simulated on the host PC through digital to analogue conversion and necessary amplification stages as shown in figure 4-5 while the trip signal generated by the relay is received by the system through required conversions.

5. CHAPTER 5- Software Simulations of Protection Elements and Coordination

5.1. Software results and analysis

This chapter entails the theory of operation and settings, software simulation results and analysis for the particular generator protective functions studied in this thesis as well as their coordination with respective excitation limiters. The protection element functions analysed are over excitation (24), over voltage (59), under voltage (27) and field failure (40). Different operation and protection settings configured on the software multifunction generator relay are presented in this chapter. Case studies conducted on excitation limiter functioning when coordinated with respective protection elements are also entailed.

5.1.1. Steady state operation

Initially the machine is run and tested for stability. Under this condition, the generator supplies 0.9 p.u. of active power and 0.436 p.u of reactive power operating at 1.0 pu machine terminal voltage. Figure 5-1 illustrates the machine output parameters plotted against time when the system is stable. The parameters shown are the machine terminal voltage, field current, active and reactive power.

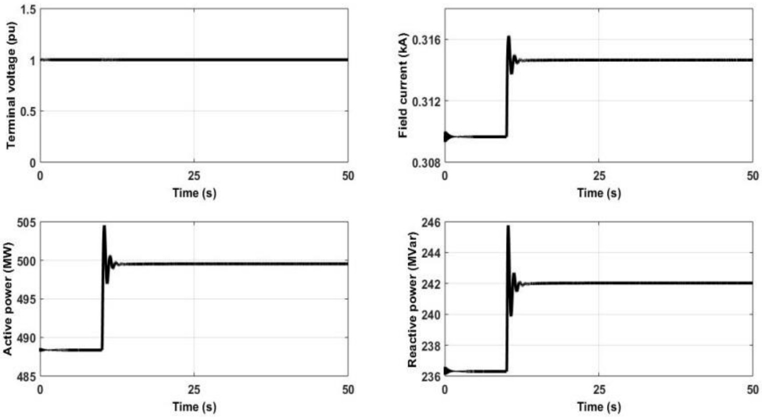

Figure 5-1: Machine stable operation

The generator circuit breaker and trip signals are shown in figure 5-2. Under normal conditions, the circuit breaker is closed and represented by logic 1 as illustrated and there is no trip signal (logic 0). In case of any fault, the breaker and trip signal will have transitions.

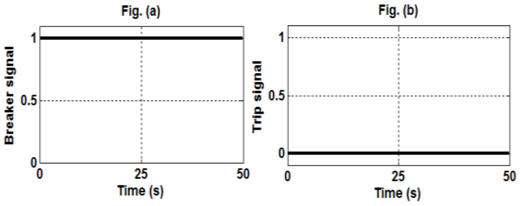

Figure 5-2: Generator breaker and trip signals

5.1.2. Over excitation (24)

The volt per hertz element is suitable for providing over excitation detection on generators. The software relay provides two elements for volts per hertz detection; the first element provides an alarm signal when setting threshold is exceeded and the second element trips the system. The relay uses the maximum phase voltage and calculates the ratio of volts per hertz and compares this to the setting thresholds. If the thresholds are exceeded longer than the time delay the element operates [54].

5.1.2.1. Relay settings

The first element uses a definite time delay while the second element can be a definite time delay or inverse time characteristic. Level 1 is set at 105% above the rated V/Hz ratio whereas level 2 is set 110% with intentional time delays which will issue an alarm signal and trip signal respectively once the V/f ratio exceeds the corresponding set values.

5.1.2.2. Level 1 simulation results

Figure 5-3 is an illustration of machine parameters when the machine was tested for level 1. The machine was run at 106% which is above level 1 pickup setting, the V/Hz ratio measured at this level was 105.1%; an alarm signal was then issued as a warning following a time delay measured by the time counter in RSCAD runtime. At constant frequency, the machine terminal voltage is the same the V/Hz ratio as shown in figure 5-3 (a). The field current, active power and reactive power output at 106 % are shown in figure 5-3 (b), (c) and (d) respectively. Figure 5-4 illustrates the alarm signal issued at 106% excitation level.

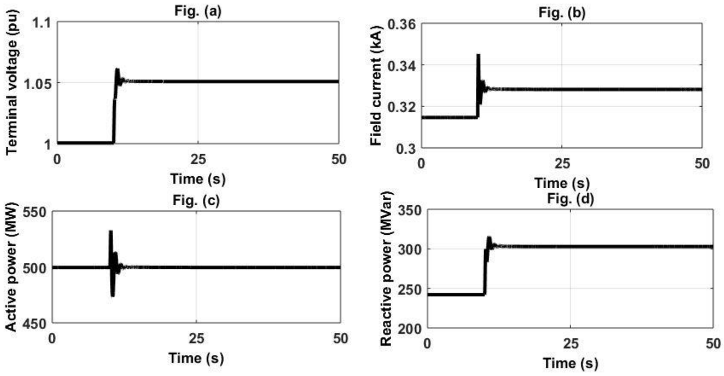

Figure 5-3: Machine parameters at 106 % excitation

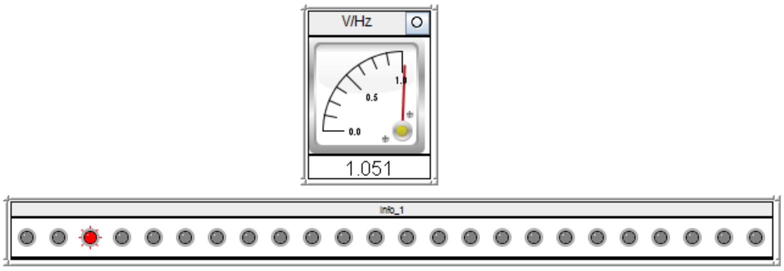

Figure 5-4: Alarm signal after level 1 detection

Increasing the excitation level above the normal operating setting increases the terminal voltage and the field current which then increase the machine reactive power. The active power delivered by the machine remains intact.

5.1.2.3. Level 2 simulation results

Level 2 is tested by running the machine at 111.4% above its normal excitation level while the relay is set to pick up at 110% with desired time delay. The second level trips the generator. Figure 5-5 illustrates the machine output parameters such as the machine terminal voltage, field current, active and reactive power during level 2 testing.

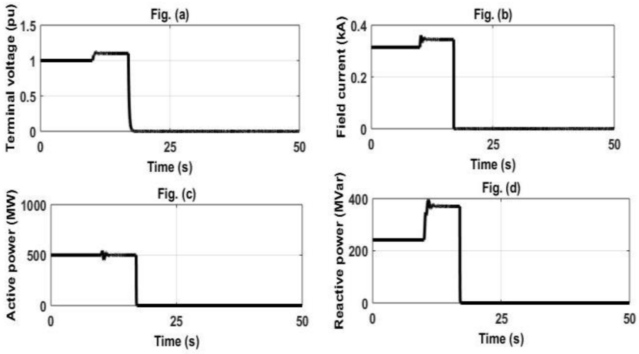

Figure 5-5: Machine output parameters at 111.4% excitation

As mentioned in level 1 testing, increasing excitation levels increases machine terminal voltage and hence the V/Hz ratio at constant frequency. With the increase in the V/Hz ratio above the level setting, the relay issues the trip signal after the delay time has elapsed. The level 2 setting was detected when the V/Hz setting was slightly above the machine setting (figure 5-5 and 5-7). When the relay tripped all the machine output parameters went to zero as the machine shuts down. The generator breaker opens at the instance where the trip signal is issues to isolate the machine from the overexcitation operation. This relay and breaker operation is illustrated in figure 5-6.

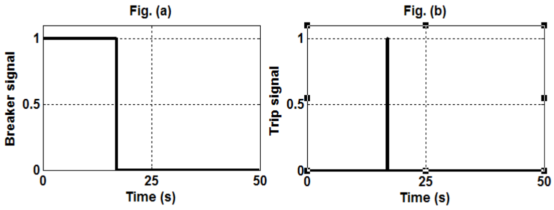

Figure 5-6: Breaker and trip signals for level 2 testing

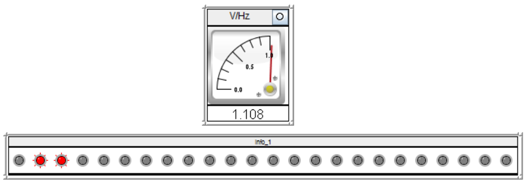

Figure 5-7: Alarm and trip signals after level 2 detection

5.1.3. Over voltage (59)

The overvoltage element is suitable for providing detection of overvoltage conditions and providing backup protection. Overvoltage conditions are usually the result of a sudden loss of load. Small overvoltages cause large increases in excitation field current and cause overheating [4]. For these reasons, the generator should be provided with over-voltage protection, either using time delayed element, inverse definite minimum time or definite time. The time delay should be chosen that it is long enough to prevent operation during normal regulator action and hence AVR and its transient response should be taken into account [55].

5.1.3.1. Relay settings

A generator can be protected from over-voltage by using following types of over-voltage protection schemes [56]:

- Using over-voltage relay function with inverse time characteristics and instantaneous in which the pickup setting of the inverse time element is set at about 110% of generator rated voltage and a time-voltage curve is chosen which provides a desired operating time at 140% of the pickup setting while the instantaneous element is set at 130% to 150% of generator rated voltage.
- The over-voltage protection with two stages of pickup value with definite time relays based on the generator manufacturer's recommendation in which the first stage is set at 110% of generator rated voltage with a time delay of 10-15 seconds while the second stage pickup is set at 150% of generator rated voltage with a definite time delay of 2 to 5 cycles.
- The maximum phase voltage is chosen and compared to the first threshold; the negative sequence voltage is compared to the second threshold [54][57]. The first element is normally set for $106 - 110\%$ of nominal voltage with a delay of 10-15 s. The second element has a quicker time delay [54][57]. The second level is set between 120 -150% of the nominal voltage with a shorter time delay.

5.1.3.2. Level 1 simulation results

The generator was to set to run at 111.4% of rated voltage when the relay pick up setting for level 1 was 110%. The terminal voltage, field current, active and reactive power output is shown in figure 5-8(a), 8(b), 8(c) and 8(d) respectively. Both overvoltage level settings trip the generator. Figure 5-9 illustrates the relay operation for circuit breaker control during level 1 over voltage trip.

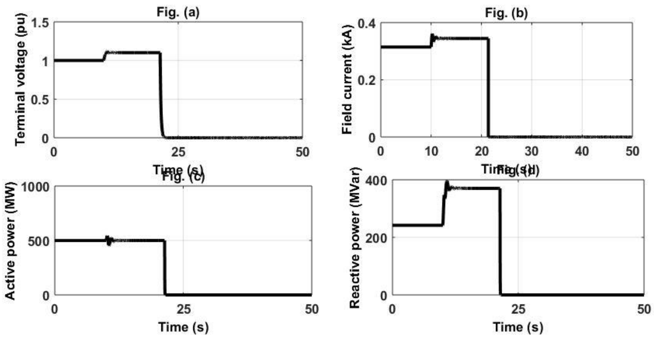

Figure 5-8: Over voltage level 1 system behavior

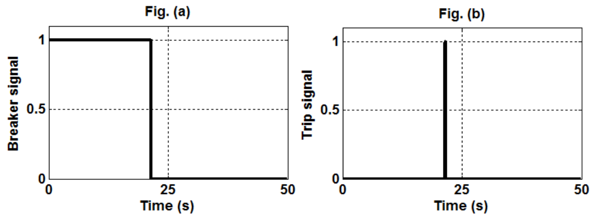

Figure 5-9: Breaker and trip signal during over voltage level 1 testing

5.1.3.3. Level 2 simulation results

The level 2 relay threshold setting of 150% with a desired time delay is used. The generator was operated at 151.9% for the second level testing and the generator parameters obtained under this operation are shown in figure 5-10.

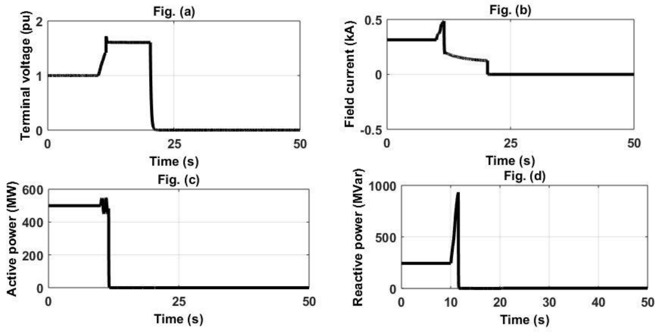

Figure 5-10: System behavior during over voltage level 2 testing

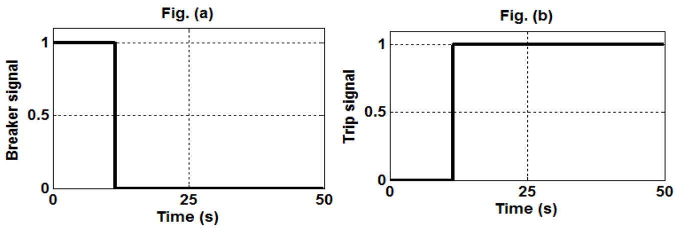

Figure 5-11: Breaker and trip signals during over voltage level 2 testing

Figure 5-11 illustrates the breaker and trip signals when level 2 testing was conducted. Since level 2 was set with a quicker time delay, the relay sends a trip signal much quicker compared to level 1.

5.1.4. Under voltage (27)

Under-voltage condition can arise due to sudden increase in load on the generator, fault conditions in nearby system, failure of automatic voltage regulator etc. [58].

5.1.4.1. Relay settings

The minimum phase voltage is chosen and compared to the setting thresholds. The first element is normally set for 90 − 95% of nominal voltage with a time delay of about one second. The second element is normally set for 80% of nominal voltage with a quicker time delay [54].

5.1.4.2. Level 1 simulation results

To test the generator under voltage level 1, the generator was operated at 89.5% of rated voltage below the 90% set level. When level 1 was detected, the machine started drawing the reactive power (figure 5-12(d)) while active power remains the same. The decrease in reactive power forces terminal voltage of the machine also to decrease below the undervoltage level 1 setting threshold in the relay. As the level detection persists, a trip signal is sent (figure 5-13) and the generator shuts down.

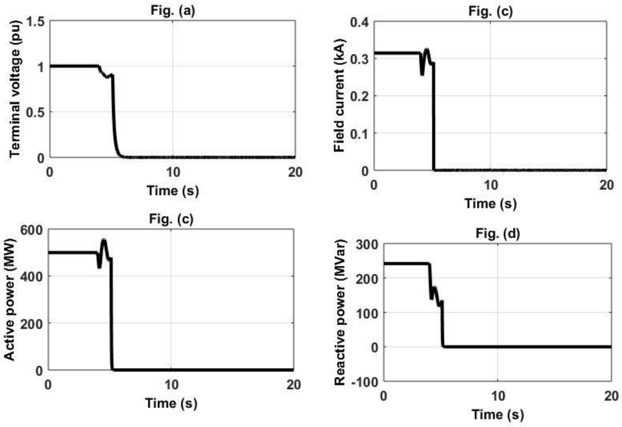

Figure 5-12: System behavior during under voltage level 1 testing

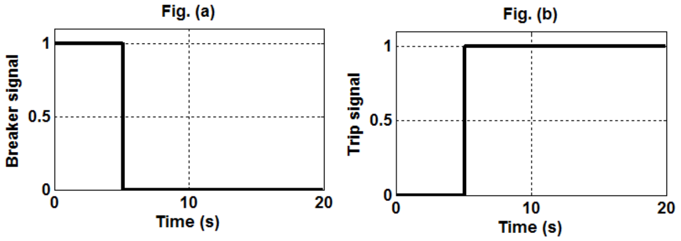

Figure 5-13: Breaker and trip signal during under voltage level 1 testing

5.1.4.3. Level 2 simulation results

Level 2 is tested by operating the generator at 79.39% of the rated voltage while the pickup setting of the relay is 80%. The system behaviour and the breaker and trip signals during level 2 testing of the undervoltage relay is shown in figure 5-14 and 5-15 respectively.

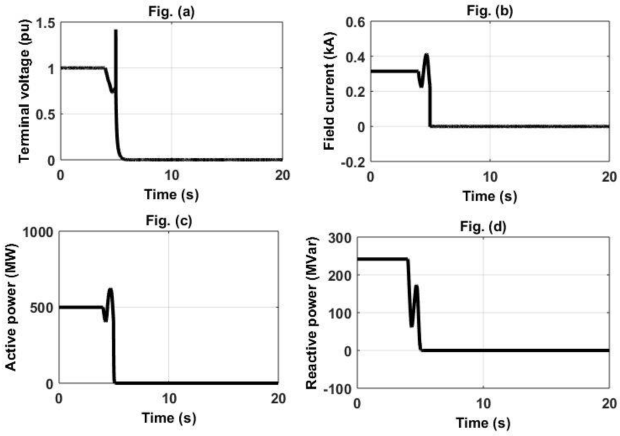

Figure 5-14: System behavior during under voltage level 2 testing

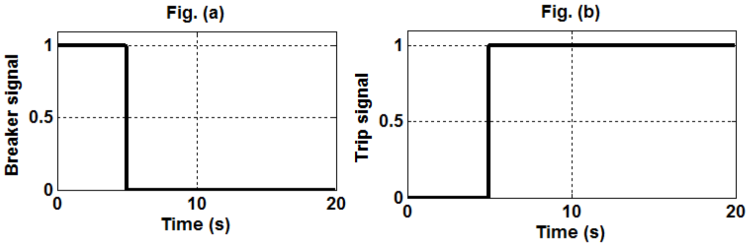

Figure 5-15: Breaker and trip signals during under voltage level 2 testing

5.1.5. Loss of field excitation (40)

Generator excitation systems are mainly for reactive power flow control and synchronism of the generator to ensure continuous active power transfer. Field failure is an undesirable condition on generators; therefore it needs adequate protection that will isolate the machine as quickly as possible to avoid damages which may result thereafter. The generator software relay consists of mho characteristic with two levels of field failure detection.

5.1.5.1. Relay settings

Two offset mho relay characteristics are used in this element. The relay uses the current and voltage transformer secondary quantities to calculate the impedances. From the generator parameters impedance and offset relay settings are obtained. Zone 1 time delay is set to prevent misoperation during switching transients whereas zone 2 time delay is used to avoid relay misoperation during power swing conditions.

5.1.5.2. Simulation results

Figure 5-16 illustrates the system behavior when zone 1 operation was tested. The rotor speed increases, active power output decreases, and the generator draws reactive power from the system. High currents are induced in the rotor and stator which can cause dangerous overheating in a very short time. Proper protection schemes can be of great importance in mitigating such conditions in generators. With more reactive power being drawn from the system, the terminal voltage of the machine reduces. Figure 5-17 illustrates the breaker and trip signals during zone 1 field failure.

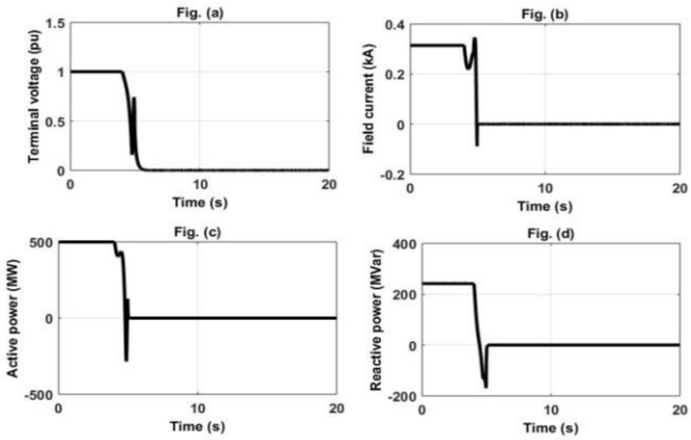

Figure 5-16: System behavior during zone 1 level detection

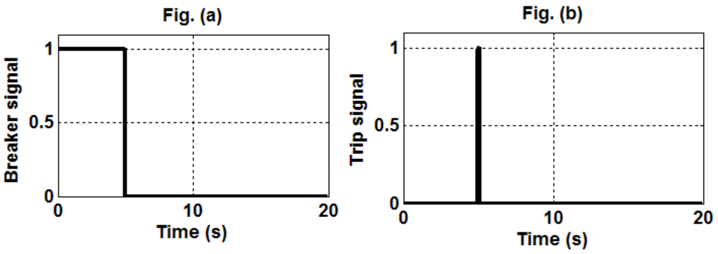

Figure 5-17: Breaker and trip signal during zone 1 level testing

Both zone 1 and zone 2 trips the generator. Zone 1 trip from heavy load conditions whereas zone 2 detects light load conditions.

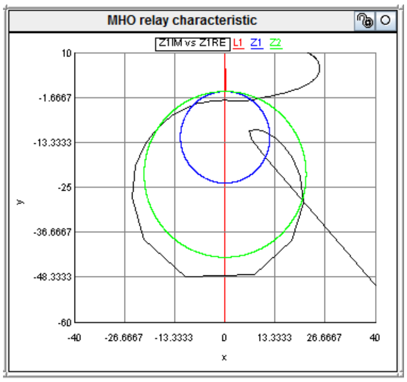

Figure 5-18: MHO relay characteristic for zone 1

Zone 1 and zone 2 MHO relay characteristics are shown in figure 5-18 and figure 5-21 respectively. When the excitation was reduced beyond minimum limits, the voltage to current ratio is reduced causing the generator positive sequence impedance measured at the stator terminals to decrease and enter the fourth quadrant of the R-X plane where it terminates inside the circular characteristic of the MHO relay characteristics, causing the relay to detect loss of field excitation. Figure 5-19 shows the system parameters during zone 1 trip.

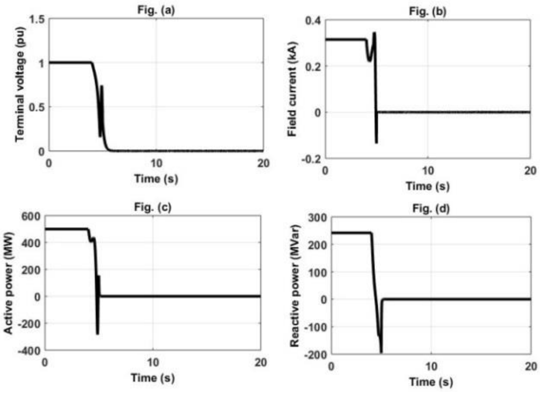

Figure 5-19: System behavior for zone 2 level testing

Each zone level trip is detected by the respective bit signal coming from the relay specifically indicating which relay has operated. This is to ensure that the user is aware which relay has operated since the software relay is multifunctional. Breaker and trip signals are illustrated in figure 5-20 under each zone test.

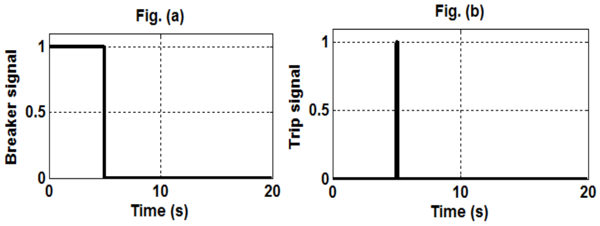

Figure 5-20: Breaker and trip signal for zone 2 level detection

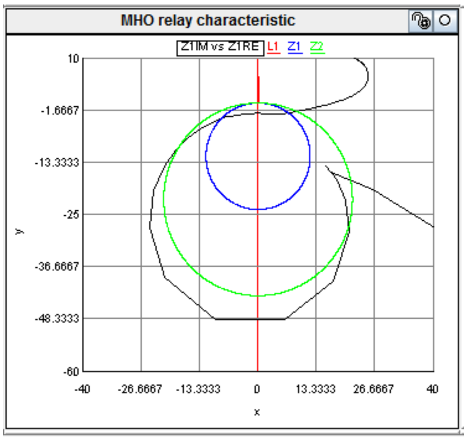

Figure 5-21: MHO relay characteristic for zone 2 level detection

5.2. Excitation limiter and coordination

Excitation limiters play a vital role in power system voltage studies and protection. As discussed in chapter 2, the limiters are embedded in AVR to limit or to ensure that the generator operates within its thermal capability limits. The action of the limiter in the AVR system takes priority whenever there is a disturbance in the system parameters. The limiters presented are modelled and tested as part of one case study, and thereafter coordinated with respective protection elements.

Excitation limiters and protection takes into account parameter and time settings for adequate operation. Coordination is mainly achieved through proper magnitude and time delay settings.

5.2.1. V/Hz limiter

The limiter controls the V/Hz through field voltage control. This is done to ensure that the ratio does not exceed a preset value. Figure 5-22 shows the voltage to frequency overexcitation limiter model. When the ratio exceeds the pre-set limiting value, a strong negative signal drives the excitation down. The limit is set typically below the overexcitation trip level of 110%.

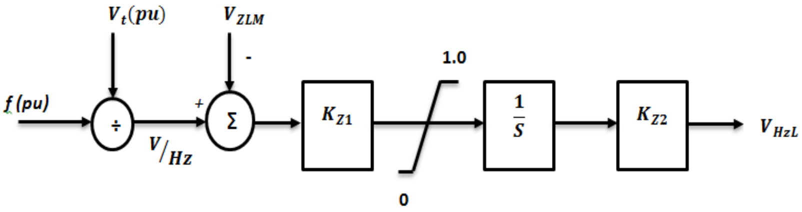

Figure 5-22: V/Hz limiter model

5.2.1.1. V/Hz limiter testing

The output remains at zero when the limiter is not operating as illustrated in figure 5-23. When it starts operating, the output changes from 0 to any positive value depending on how much the system is overexcited. This action takes control in the AVR and drive the excitation down to acceptable levels. Under normal operation conditions when the limiter is not in operation the active and reactive power delivered are shown in figure 5-24.

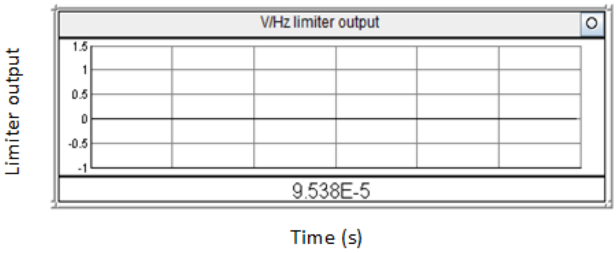

Figure 5-23: V/Hz limiter output operation

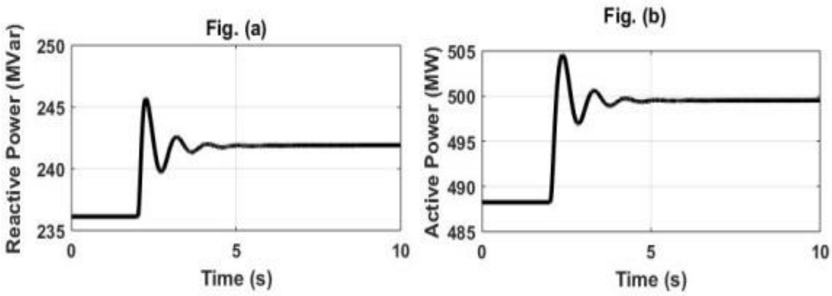

Figure 5-24: System before limiter operation

5.2.1.2. V/Hz limiter and V/Hz protection coordination

The minimum threshold setting of the limiter is 105%; it can be seen in figure 5-25 that when the system was run at 104%, the terminal voltage of the machine increased by the same percentage but the limiter output remained at 0 as expected.

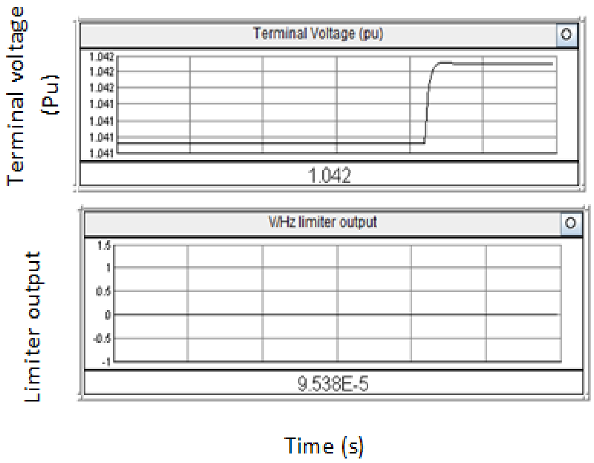

Figure 5-25: V/Hz limiter testing

After testing the limiter, the machine is run at two different overexcitation levels to observe the performance of the limiter. The set of results in figure 5-26, 5-27 and figure 5-28 show the system behavior at 106% and 111% excitation levels respectively.

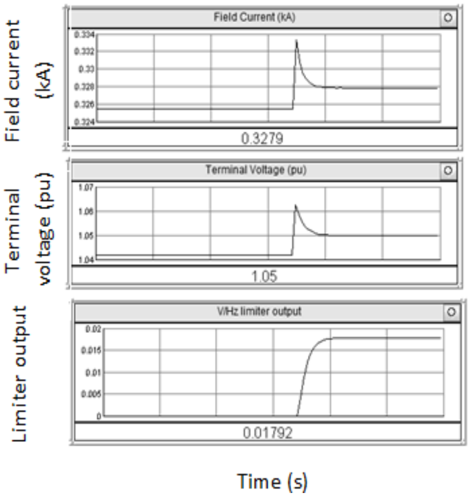

Figure 5-26: System parameters at 106%

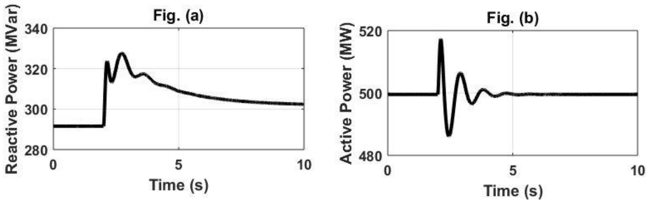

Figure 5-27: Active and reactive power at 105% excitation level

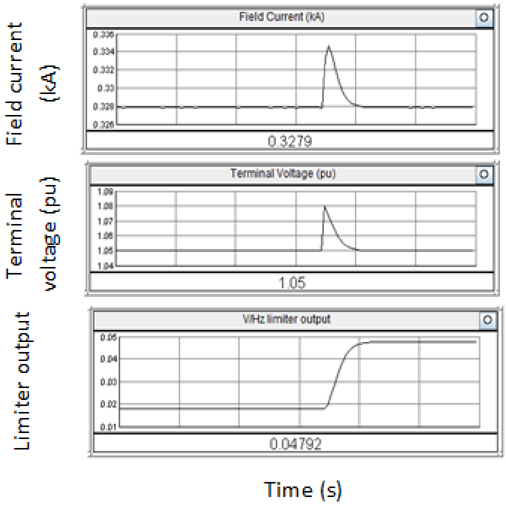

Figure 5-28: System parameters at 111% excitation

In both cases, the limiter takes control in the AVR to reduce the excitation voltage to a safe value of 105%. However, one of the fundamental observations of this limiter is that it will always prevent the increase in the excitation level of the system. A typical example to this is shown in figure 5-28; the excitation level was 111% but the system voltage could only increase up to about 109%.

Furthermore, when level 2 was tested without the V/Hz limiter, the relay tripped the machine when 110% level setting was reached which is different in the presence of the limiter. When the machine was run at 111% the limiter drove the excitation down to 105% as per the V/Hz limiter model. Overexcitation element (24) is enabled as a backup of the system. As a result, when the system was run at 120% the system conditions prevailed longer than the relay level 2 setting threshold of 110% the relay operated. This is shown in figure 5-29 and 5-30 with the relay operation in figure 5-31.

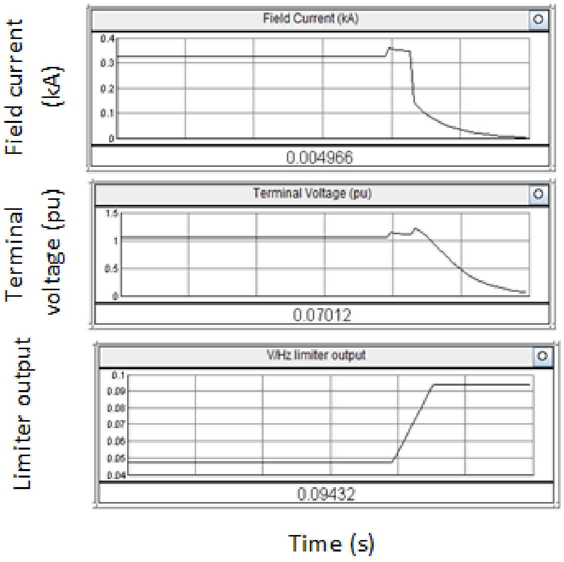

Figure 5-29: System operation above relay pickup setting

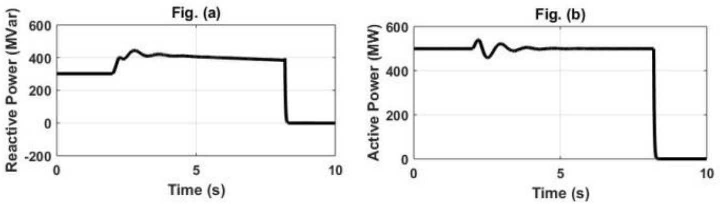

Figure 5-30: Active and Reactive power during relay operation

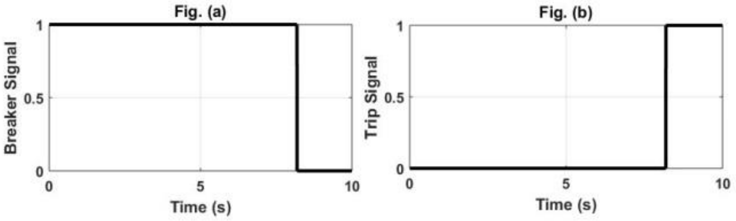

Figure 5-31: Breaker and trip signal

5.2.2. OEL

The operation of overexcitation limiters is similar; the only difference is how they are modeled. OEL limits the excitation system from supplying excess field. The modelling of the over excitation limiter considers field current as inputs to the limiter, the field current of the machine is measured and compared with the limiter setting thresholds.

When not in operation, the limiter output is zero, as excitation levels changes the output of the limiter changes continuously. Depending on the excitation levels, the limiter will operate and drive the excitation down to acceptable levels. Figure 5-32 illustrates the OEL limiter, field current is used as an input parameter in modelling the limiter.

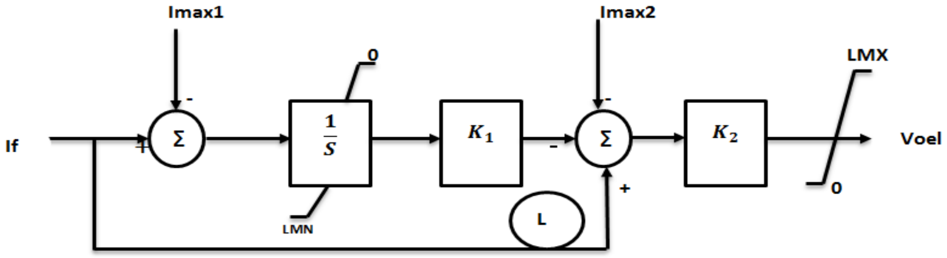

Figure 5-32: OEL Limiter model

5.2.2.1. OEL limiter testing

Under system healthy conditions, the output of this overexcitation is 0 as illustrated in figure 5-33. Other system parameters such as the machine active and reactive power, speed and torque are shown in figure 5-34.

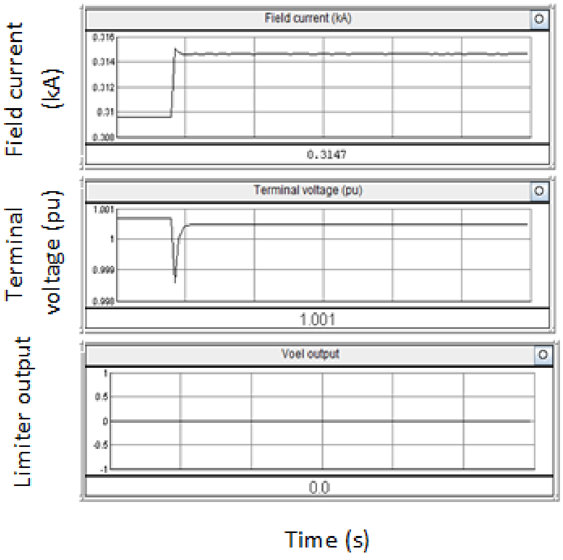

Figure 5-33: OEL operation

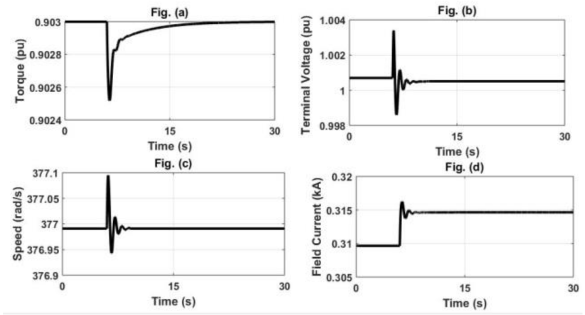

Figure 5-34: System parameters under normal operation

The limiter is set to pick up above 105% like the V/Hz limiter; excitation levels below 105% will not have any effect in the limiter output or the AVR. Same testing is done to observe the operation of this limiter. The system is run at 104% and the system parameters are shown in figure 5-35.

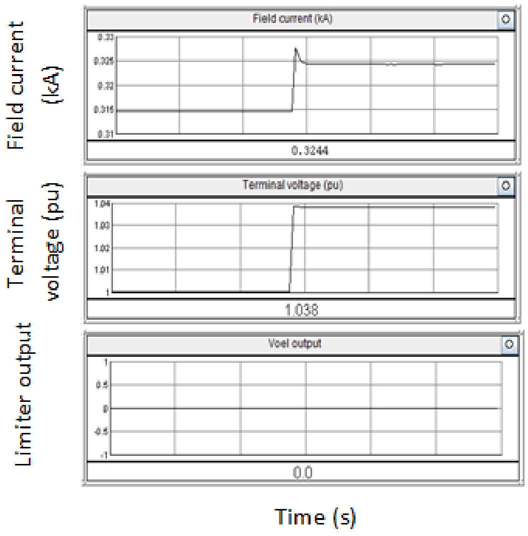

Figure 5-35: System operation below limiter pickup

5.2.2.2. OEL and overexcitation protection coordination

Overexcitation (24) and overvoltage (59) elements are used as backup protection and for coordination. The machine was run and tested for three different excitation levels with the OEL limiter in operation. When testing over voltage or overexcitation protection, ideally 110% is set as a trip level pickup setting for the relay. However, with the limiter in operation, this is different. Figure 5-36, 5-37 and 5-38 illustrate the system parameters and the limiter output when the machine was excited by 110%, 130%, and 140% respectively.

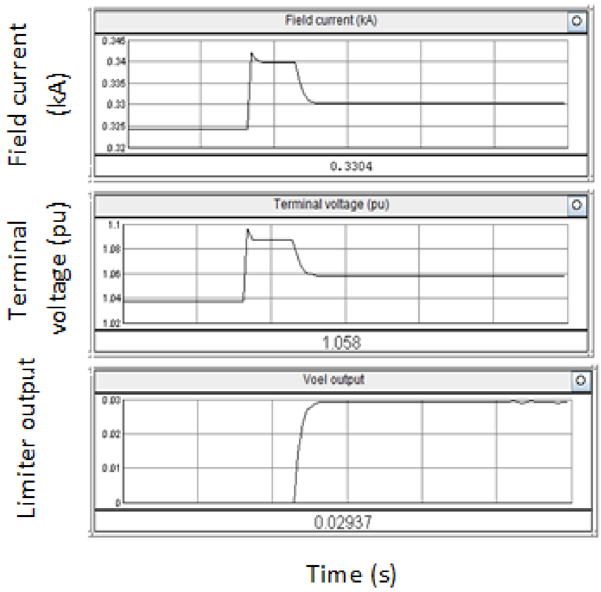

Figure 5-36: System parameters at 110% excitation level

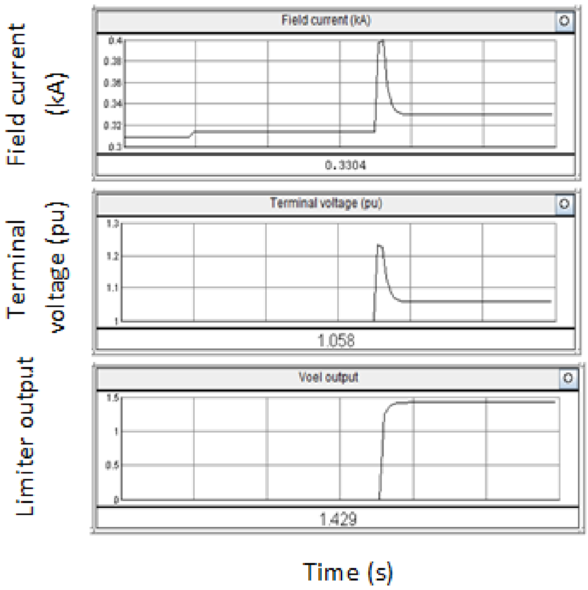

Figure 5-37: System parameters at 130% excitation

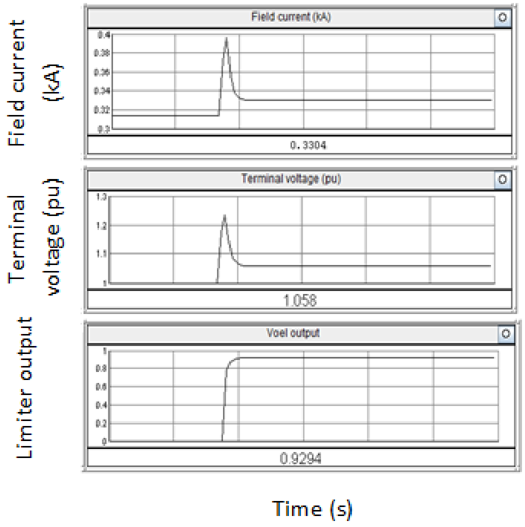

Figure 5-38: System parameters at 140% excitation

From the results obtained, the limiter is able to drive down the excitation back to an acceptable level of 105% with an error of 0.76% which is due to estimation of the limiter model parameters.

5.2.3. Underexcitation limiter

The operation of the underexcitation limiter is complex compared the overexcitation limiters. In this thesis, the straight-line characteristic model is utilized for simulation studies. The testing of UEL in the underexcitation region involves a number of stages. Initially, the limiter is modeled and tested using parameter estimation scheme. This is done mainly because the operation or modeling of the limiter differs depending on the system being used, the rating of the machine etc. The idea is to estimate the limiter parameters that will best achieve the stable operation condition of the machine.

5.2.3.1. Underexcitation limiter testing

The system is initially run at full load to test conditions before implementing underexcitation. Because this is underexcitation operation, the system is forced to operate in the underexcited region, absorbing reactive power. This is illustrated in figure 5-39. The initial parameters under this condition differ; the machine is now operated at -0.006pu reactive power with a terminal voltage of 0.93pu.

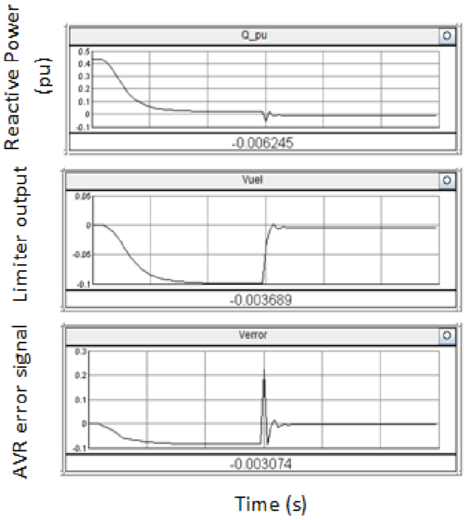

Figure 5-39: System parameters in the underexcited region

To validate the model and its parameters, the system is operated at different reduced excitation levels and the temporal changes of the variables Vuel, Verror and Q are recorded and illustrated in figure 5-40, 5-41, 5-42 and 5-43.

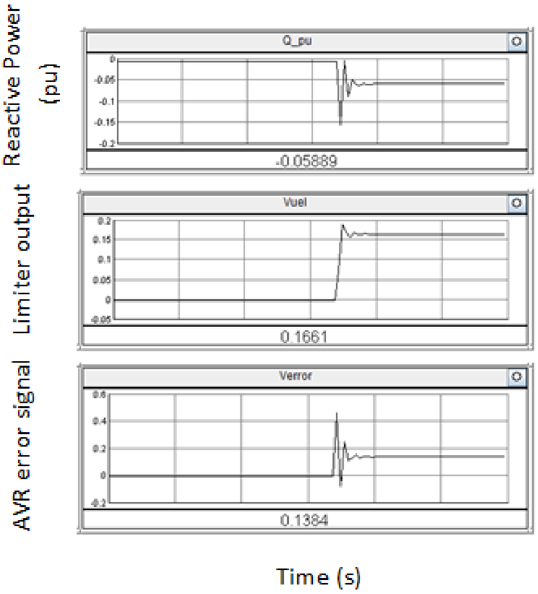

Figure 5-40: Limiter operation at 90%

The limiter output and Verror signals from the limiter model are compared with the output signal at the AVR summing junction, the highest value takes control of the AVR and brings the limiter into operation. Once the limiter operates the error signals from the limiter model and the AVR transits and the change of signs verifies the operation of the limiter, specifically the limiting characteristic.

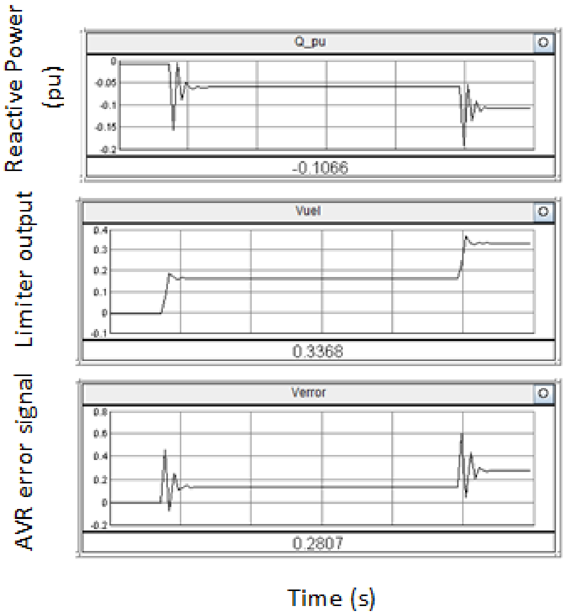

Figure 5-41: system operation at 70% excitation level

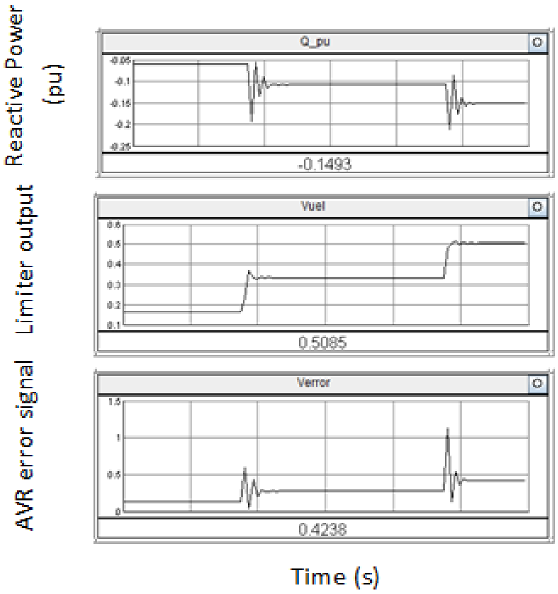

Figure 5-42: system parameters at 50% excitation

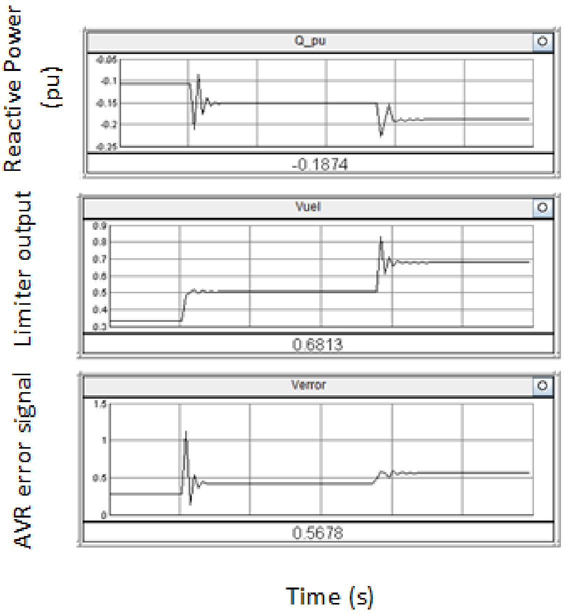

Figure 5-43: System parameters at 30% excitation

The limiting characteristic of the machine is also plotted in the P-Q plane to verify the straight-line characteristic UEL model as illustrated in figure 5-44.

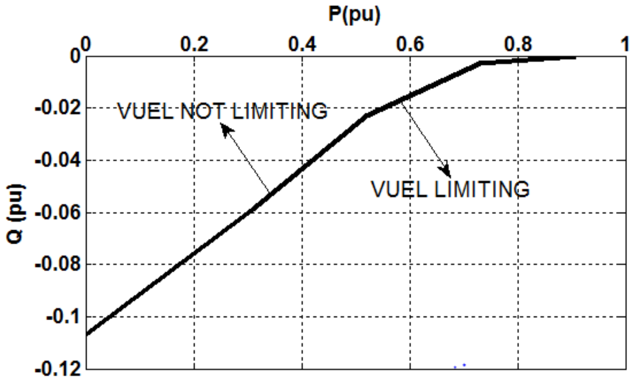

Figure 5-44: UEL limiting characteristic

5.2.3.2. Limiter operation and coordination with field failure and undervoltage relays

The field failure and the undervoltage relays are used as backup protection in the underexcitation operation region. The idea is to verify the operation of UEL when coordinated with generator protection. Initially the same procedure of running the generator where it absorbs reactive power is employed. Figure 5-45 illustrates the system parameters under this condition.

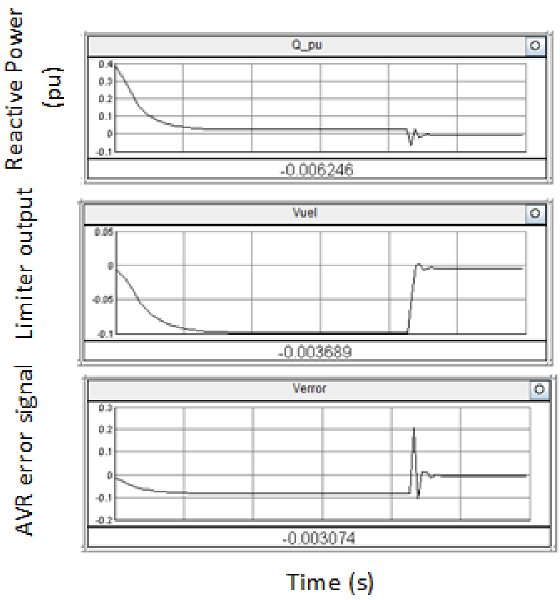

Figure 5-45: System parameters in the underexcited region

The relay is set to allow the field failure operation before undervoltage element. For coordination studies, three levels of underexcitation were investigated. The MHO characteristic for each level tested is illustrated in figure 5-46, 5-47 and 5-48 for 70%, 50% and 30% excitation levels respectively.

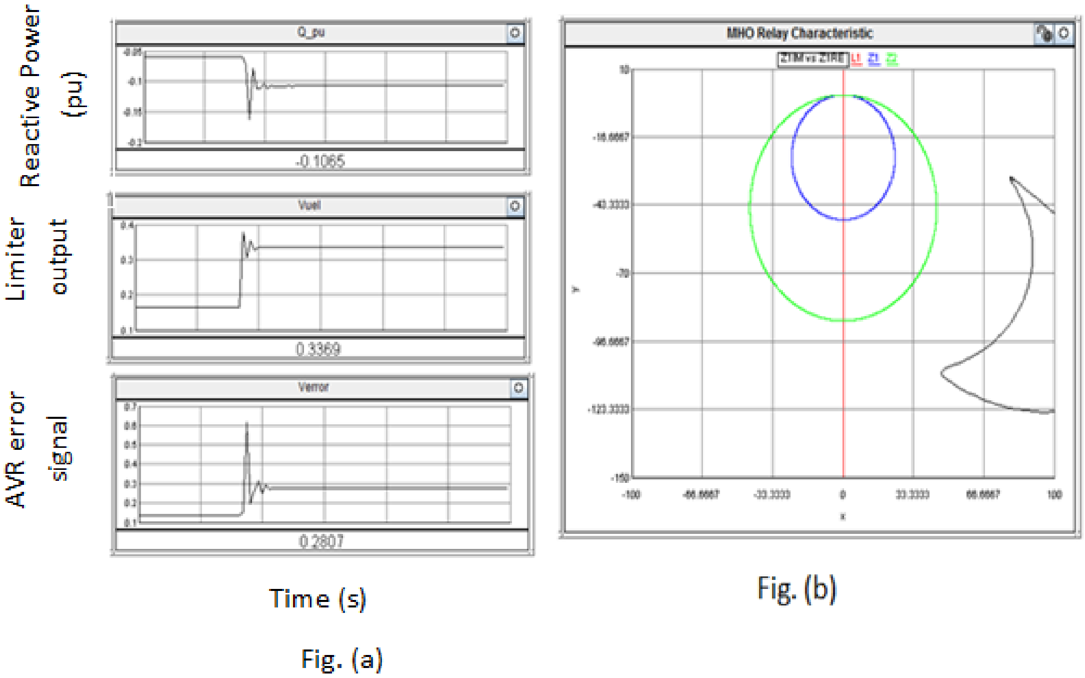

Fig. (a)

Fig. (b)

Figure 5-46: (a) system parameters at 70% excitation level (b) MHO characteristic at 70% excitation

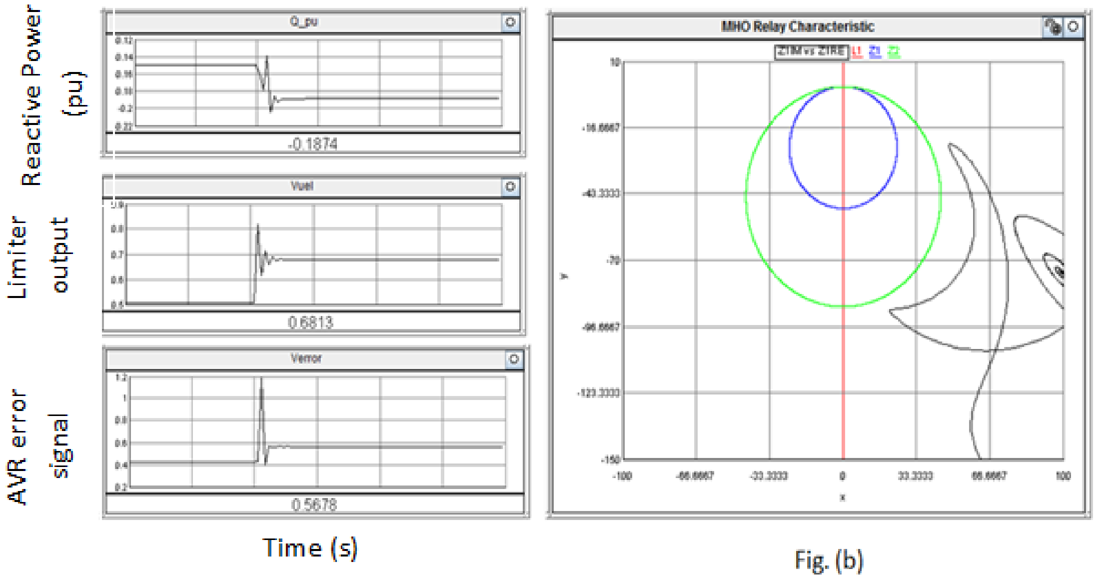

Fig. (a)

Fig. (b)

Figure 5-47: (a) System Parameters at 50% excitation (b) MHO characteristic at 50%

As the excitation level reduces, the impedance locus measured gets closer to the MHO circles and eventually enters zone 2 where field failure is detected by the relay (figure 5-48). Due to field failure, the system trips and voltage reduces, when this happens undervoltage relay operates. This is illustrated in figure 5-49 with three trip signals first from loss of field followed by undervoltage.

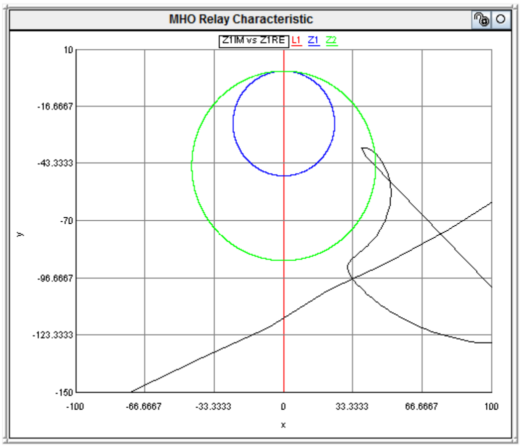

Figure 5-48: Field failure detection

The information graph of trip signals is provided by the software relay on RTDS to ensure the user knows which relay operated during any type of fault as illustrated in figure 5-49. Bit 16 and 17 represent zone 1 and zone 2 respectively whereas bit 25 and 26 represent level 1 and 2 of under voltage. Figure 5-50 shows the machine terminal voltage and active power when zone 2 field failure was detected.

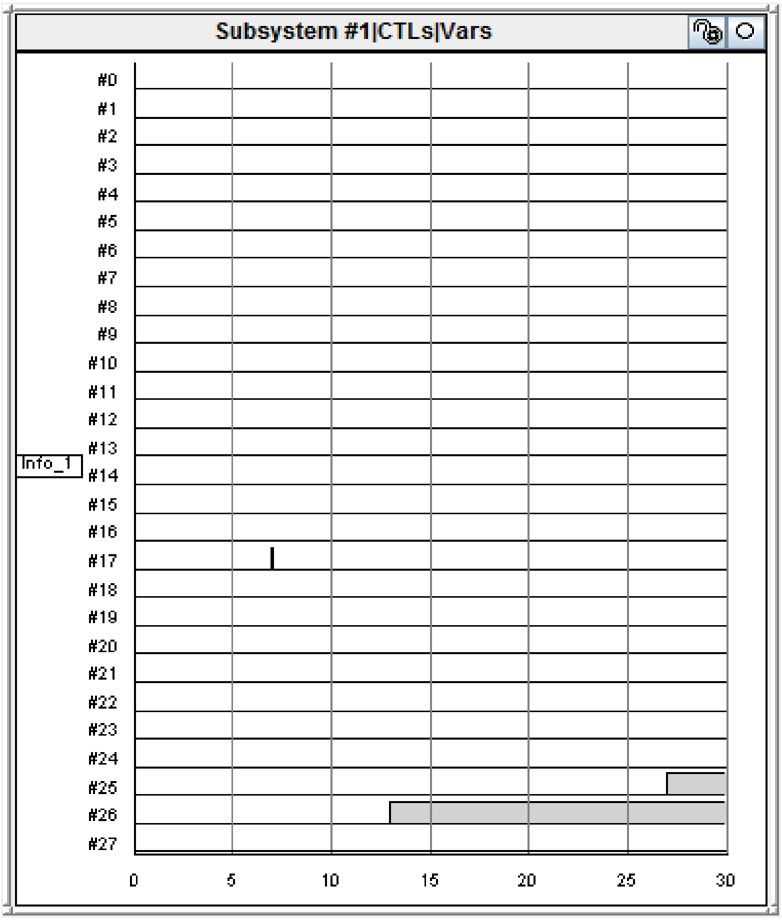

Figure 5-49: Relay elements operation

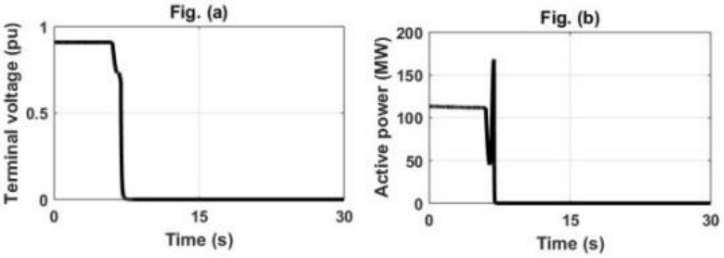

Figure 5-50: Breaker and trip signals

6. CHAPTER 6- Testing Commercial Relay for Coordination

6.1. Introduction

This chapter entails the hardware in-loop testing of generator protection using SEL-300G multifunction generator relay. The results presented in this chapter are carried out on RTDS. The relay is configured and ensured to be working properly before any element testing. The fundamental purpose of the HIL tests carried out is to verify some of the theories on generator protection, relay settings, and to compare the functioning of the generator software relay with SEL-300G commercial relay. The system used for the HIL tests is the similar system used with software relay studies. Four generator protection elements are tested i.e. Overexcitation (24), Over-voltage (59), under-voltage (27) and loss of field excitation (40) in over and under-excitation operation regions.

6.2. SEL 300G Relay

The SEL 300G relay is a multifunctional digital microprocessor based relay representing the class of devices used to protect the large generators found in power stations. This relay contains different protective functions that are implemented to protect the generator from various types of fault and system contingencies. A software tool that comes with the relay is used to configure different protection element settings within the SEL 300G generator protection relay. The user can activate or deactivate any protection elements provided by the SEL 300G relay according to the requirements of the designed protection system. However, protection against loss-of-potential (60) cannot be deactivated since its purpose is to detect any loss of signal from the voltage transformers used to measure generator terminal voltages. This element is used to trigger an alarm in order to notify the system operators in case of emergencies and can also be used block the relay from tripping when there is a situation of lost voltage transformer signal.

6.3. HIL configuration

Figure 6-1 illustrates the physical hardware in-loop connection on RTDS using SEL 300G commercial relay. The system is simulated on RSCAD software installed on the PC. The relay input is connected to the RTDS analogue /digital output and the RTDS analogue/digital output is connected to the power amplifier. The analogue/digital output of the relay is then connected with the analogue digital input of RTDS. The signal level analogue output voltages sent from the rack in real time must be converted to correctly-scaled currents and voltages for input to amplifier. In this way, the real time simulation can be used to drive the relay with the same power level currents and voltages it would experience in the field [16].

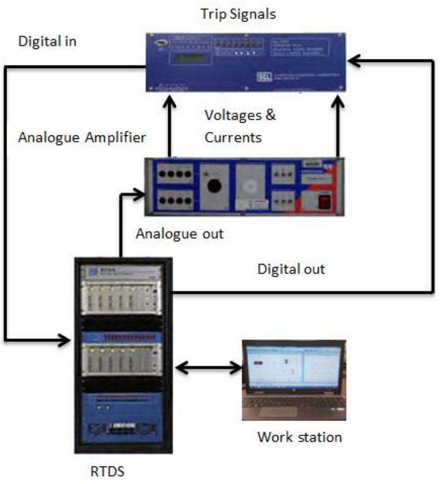

Figure 6-1: RTDS HIL connection

6.4. Simulation results and analysis

Coordination of limiters and protection elements were tested and verified in comparison with software results. Both over-excitation and under-excitation operating regions were implemented using the hardware relay to verify if the relay operation could indeed be coordinated with generator excitation limiters as presented in chapter 5. Hardware relay sensitivity is taking into consideration when implementing such studies, because any incorrect procedures may lead into great damages of the relay.

6.4.1. V/Hz limiter and overexcitation (24) coordination

Same procedures are followed during hardware in-loop testing. The relay is tested to ensure correct settings and operations and thereafter the system is tested for stability. When both conditions are met, it is then that any fault study is implemented. Figure 6-2 illustrates the machine parameters under system healthy conditions and figure 6-3 is an illustration of the voltage to frequency ratio and the V/Hz limiter output.

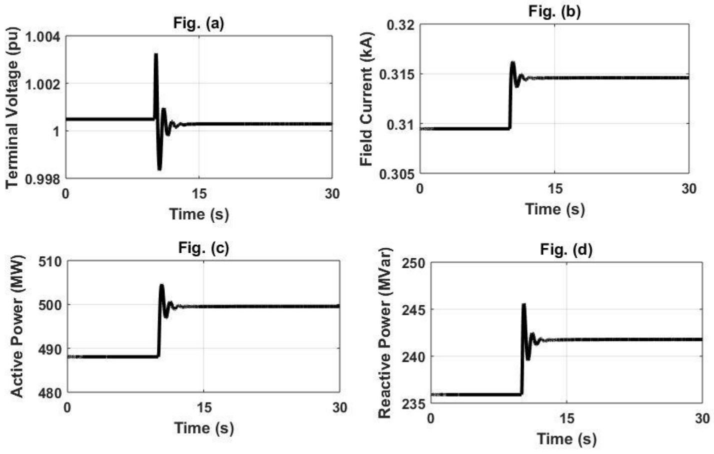

Figure 6-2: System parameters under normal operating conditions

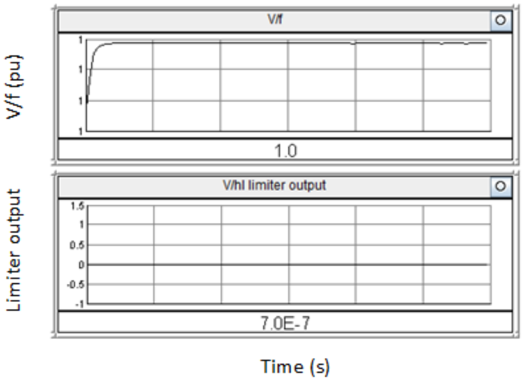

Figure 6-3: V/Hz Limiter not in operation

The overexcitation limiter used with the hardware relay is the same used with the software relay presented in the previous chapter. However, certain adjustments had to be done in the relay setting to allow the operation of the limiter when the machine is over-excited. These adjustments do not necessarily change how the limiter or the relay operates but were rather done to ensure that the settings are coordinated properly with the generator capability in the overexcited region. When the limiter was not in operation as illustrated in figure 6-3, the output to the AVR summing is zero, when there is change in the reference in the AVR; the limiter becomes more positive to drive down the excitation levels. The V/Hz limiter was coordinated with overexcitation (24) element. Same cases tested using software relay were verified using hardware.

Figure 6-4 illustrates the operation of the limiter when the machine was overexcited slightly above normal operation at 108%. It can be seen from figure 6-4 and 6-5 that the limiter took action in reducing the excitation level.

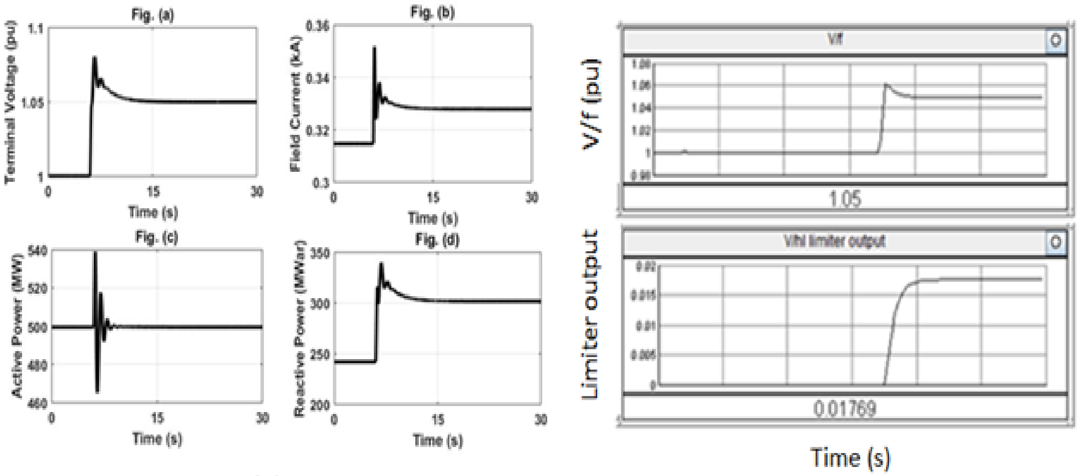

Fig. (a)

Fig. (b)

Figure 6-4: System parameters at 108% excitation level.

Based on the relay settings, at 110% excitation level the relay should operate. However, with the limiter in operation the AVR system control is able to adjust the over excitation condition to values within the machine's capability.

Stepwise over excitation testing method limits the level of overexcitation before it even reaches the maximum input by the user. This is shown in figure 6-5, the machine was excited by 112% above the normal operation, but the limiter prevented the machine excitation level increase. As illustrated, the maximum value reached is about 108.3% terminal voltage and thereafter was reduced to 105% which is within the machine capability.

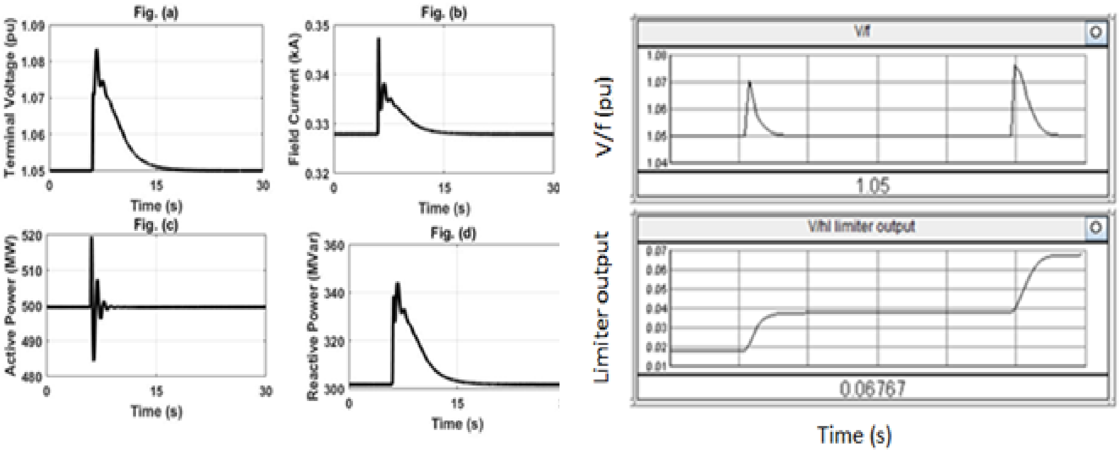

Fig. (a)

Fig. (b)

Figure 6-5: System parameters at 110% excitation level

To test whether the relay operates the machine was over excited by 120%, the limiter could only prevent this condition up to about 112% exceeding the limiter time of operation and hence the relay operated. Figure 6-6 (a) illustrates the system parameters when the relay operated. Figure 5 (b) shows the voltage to frequency ratio when the system was excited by 120% as well as the limiter operation and the breaker and trip signals are shown in figure 6-7.

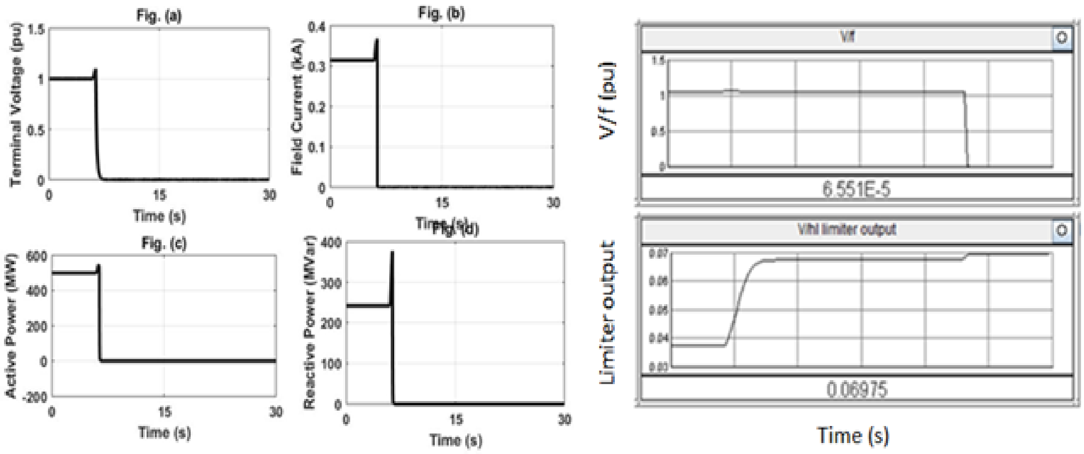

Fig. (a) Fig. (b)

Figure 6-6: System behavior when excited above 113%

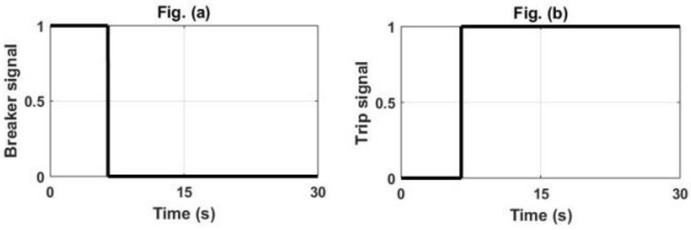

Figure 6-7: Breaker and trip signals

Figure 6-8 illustrates the hardware relay when overexcitation operated. The red light is a signal which confirms which element has operated. In this case, the trip was issued by the overexcitation (24) element.

Figure 6-8: Relay operation for overexcitation (24)

6.4.2. OEL and overexcitation (24 and 59) coordination

A 2-stage overvoltage protection element, configurable as either phase to phase or phase to neutral measuring is provided to back up the automatic voltage regulator. Stage 1 may be selected as backup protection for voltage levels above 110% and coordinated with level 2 overexcitation (24) relay which operates at 110% and above. The overvoltage relay and overexcitation are coordinated in such a way that the OEL operates before they take over. This coordination is achieved through both magnitude and time delay settings for the relays as well as the limiter.

The system is run and tested for stability before the test was implemented. Figure 6-9 shows the machine parameters under system healthy condition where the machine delivers 0.9 pu active power at 1 pu terminal voltage.

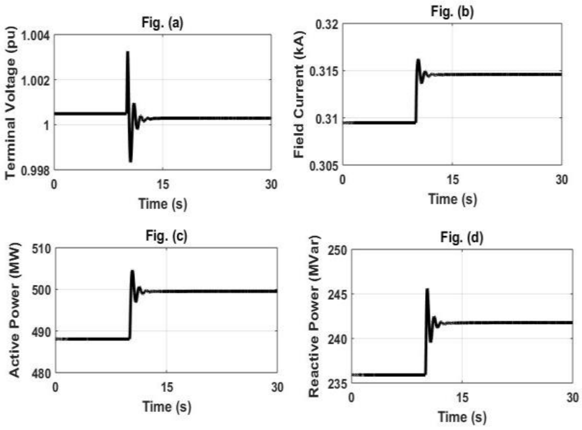

Figure 6-9: System healthy operation

Figure 6-10 illustrates the limiter output, field current and machine terminal voltage measured in runtime under system healthy conditions.

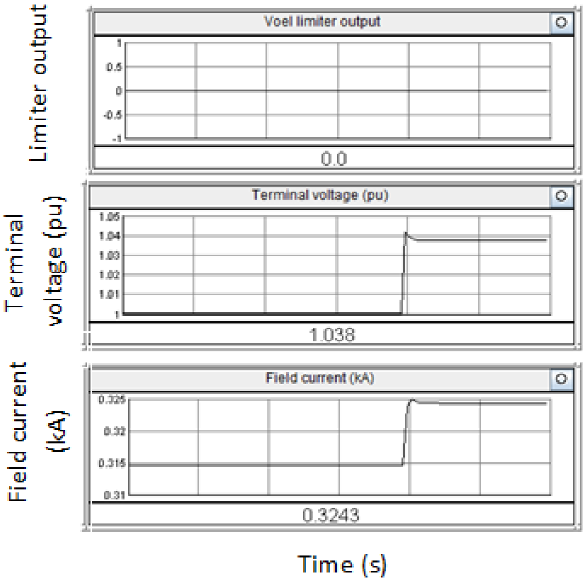

Figure 6-10: Limiter operation and machine parameters in runtime

The system is run and tested under three different overexcitation levels and results are presented. With this OEL, the excitation is always reduced to 105.8% which is the same case observed when the conditions were tested using the software relay. Figure 6-11 and 6-12 illustrates the system parameters when the machine was excited by 109% , this condition is below the trip setting for both relays and was tested to ensure the limiter was operating properly.

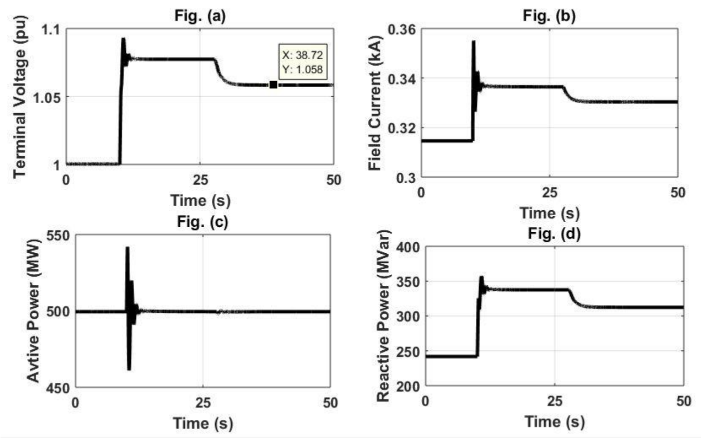

Figure 6-11: Machine parameters at 109% excitation

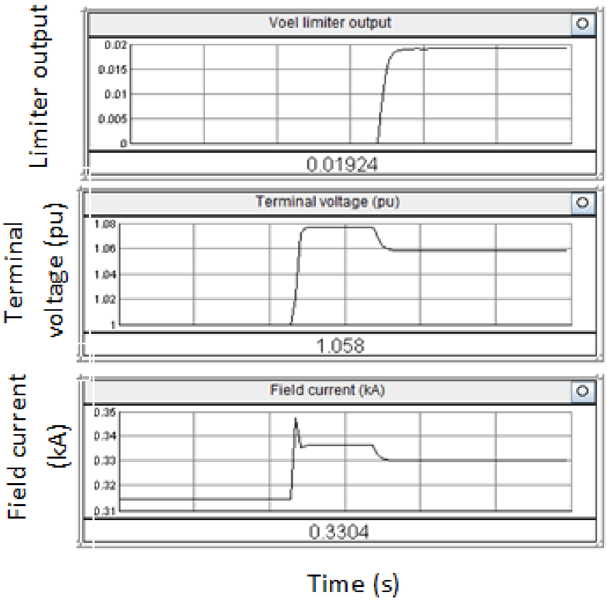

Figure 6-12: Limiter operation at 109% excitation

Figure 6-13 and 6-14 is an illustration of the limiter and machine parameters when the system was over excited by 120%. The OEL model operation is similar to the V/Hz, except that it allowed the overexcitation level up to 130% before trip. This is because of the strong counteraction in the AVR by the OEL signal at the summing junction. Irrespective of how much the machine is excited externally by the user, the limiter will always act upon the changes to ensure the machine operates within acceptable thermal limits.

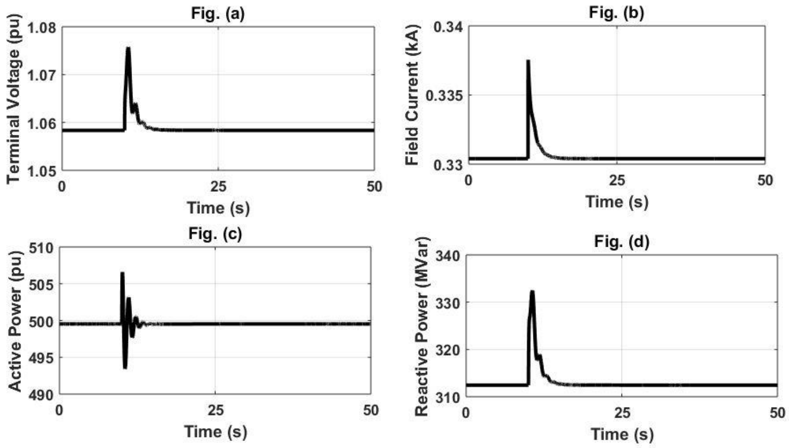

Figure 6-13: System parameters at 120 % excitation

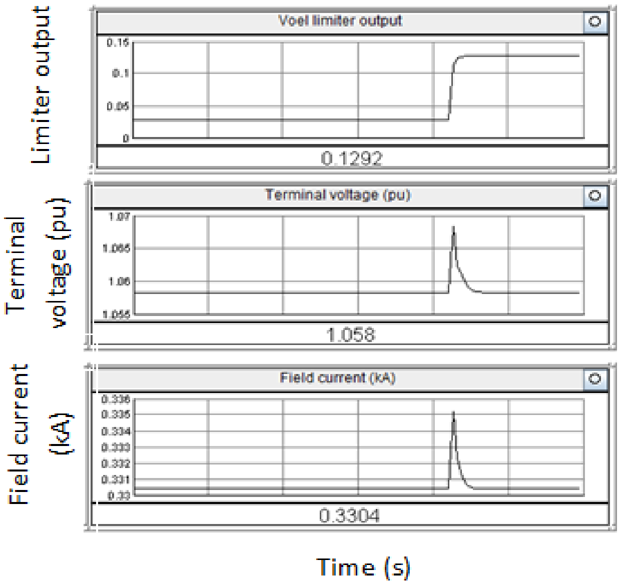

Figure 6-14: Limiter operation at 120% overexcitation

Figure 6-15 shows the machine parameters at 130 % excitation levels, it can be seen that the limiter operates to limit the field current and hence the rest of the system parameters. In runtime, the limiter output signal, field current and terminal voltage is monitored as the excitation changes. In figure 6-16, the first peak in the machine parameters is a result of 120% excitation level, few minutes later the limiter reduced the excitation level back to 105.8%. Following the operation of the limiter, the system was then overexcited by 130% and it can be seen that the limiter action prevented the increase in the excitation and later settled back at 105.8%.

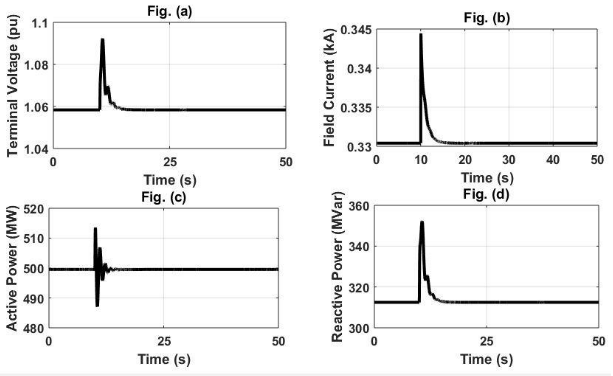

Figure 6-15: system parameters at 130% overexcitation

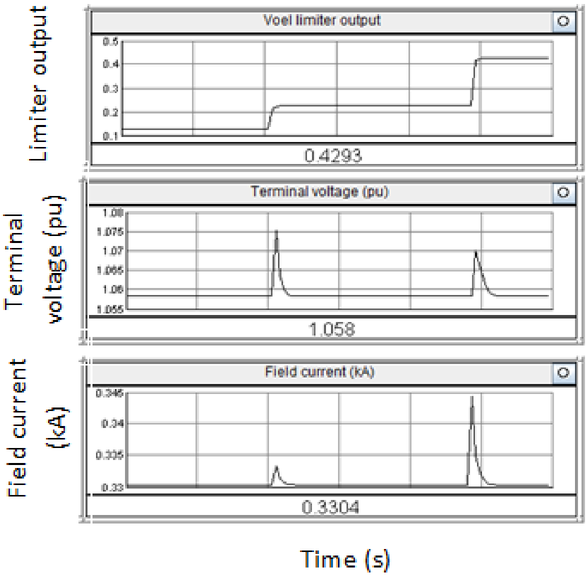

Figure 6-16: Limiter operation at 130% excitation

From how the stepwise tests were conducted, the limiter will counteract the changes in the AVR and bring the machine back to its capability. In order to test if the relay operates as backup protection, a rapid test was conducted. This means that the machine is overexcited rapidly rather than stepwise, in this case 150% overexcitation was randomly applied to the system. The OEL tried to counteract the increase but the voltage level went above the relay magnitude and time settings and hence the relay operated, detecting both over voltage and overexcitation conditions. Figure 6-17 illustrated the field current and machine terminal voltage when the relay operated.

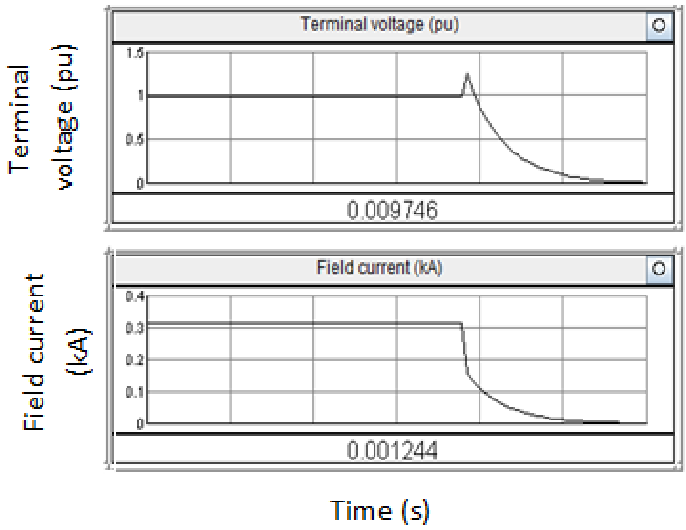

Figure 6-17: System parameters during relay operation

Figure 6-18 shows the relay operation. The settings for both overvoltage and overexcitation were similar and hence both conditions were detected and trip signals issued at the same time. Trip24 is the trip signal from overexcitation and trip59 is from overvoltage.

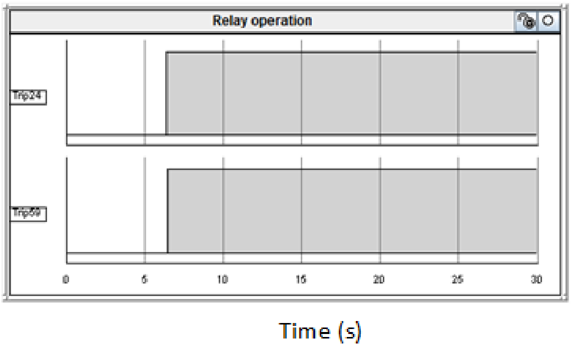

Figure 6-18: Relay operation

6.4.3. Underexcitation limiter with field failure (40) and undervoltage (27)

Field failure and undervoltage elements are configured as backup protection system during underexcitation limiter testing for coordination. Field failure is primarily coordinated with respect to underexcitation limiter in most literatures. This is done mainly because field failure is a result of prolonged underexcitation conditions. However, undervoltage can also be a result of underexcitation conditions and hence the element is also coordinated and tested with the limiter. Figure 6-19 and 6-20 illustrates the system parameters when the machine was initially run in the underexcited region. The limiter under this state remains negative as it is not operating.

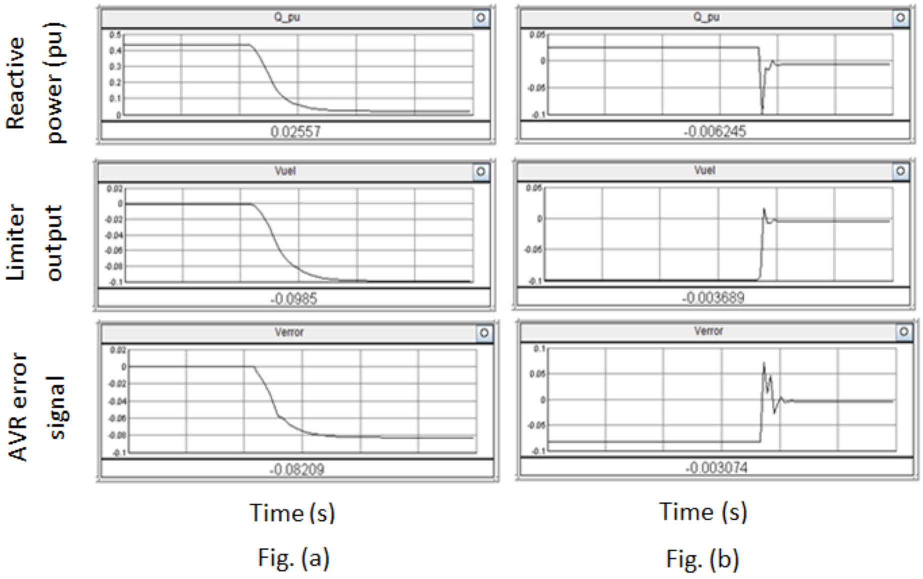

Figure 6-19: Limiter operation in the underexcited region

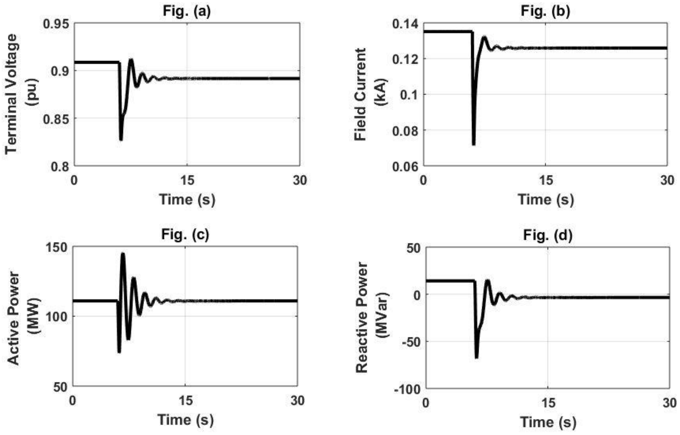

Figure 6-20: System parameters in the underexcited region

Two cases are conducted in testing the underexcitation operation. Case 1 involves testing the functionality of the limiter when coordinated with protection elements. Figure 6-21 and 6-22 illustrates the limiter operation when the machine was underexcited by 70% and 50% respectively. The operation of the limiter is the same as when the same tests were done using the software relay. The MHO characteristic at different excitation levels is shown in both figures. With the limiter operation, the system remains stable because the limiter is able to counteract the changes in the AVR system and boost excitation.

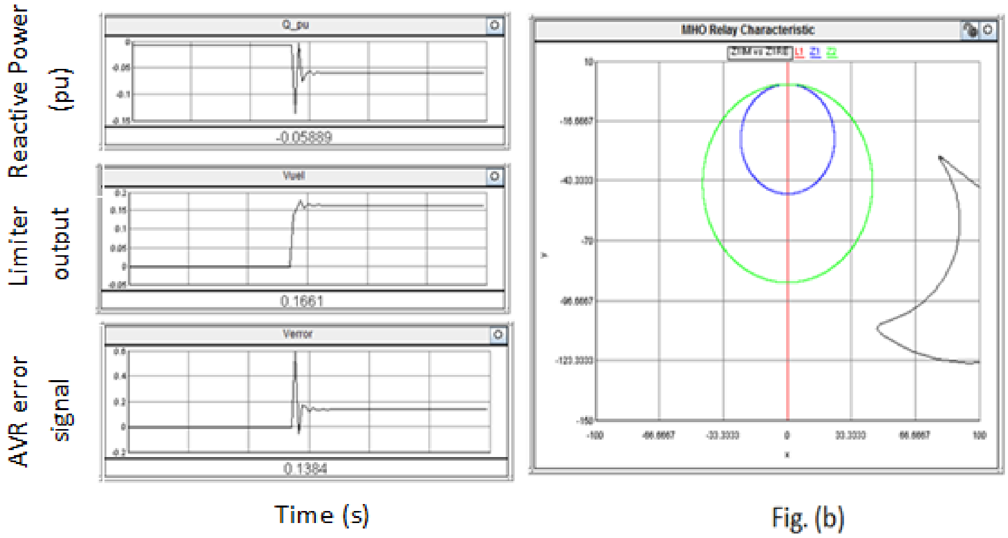

Fig. (a)

Fig. (b)

Figure 6-21: Limiter operation at 70% excitation

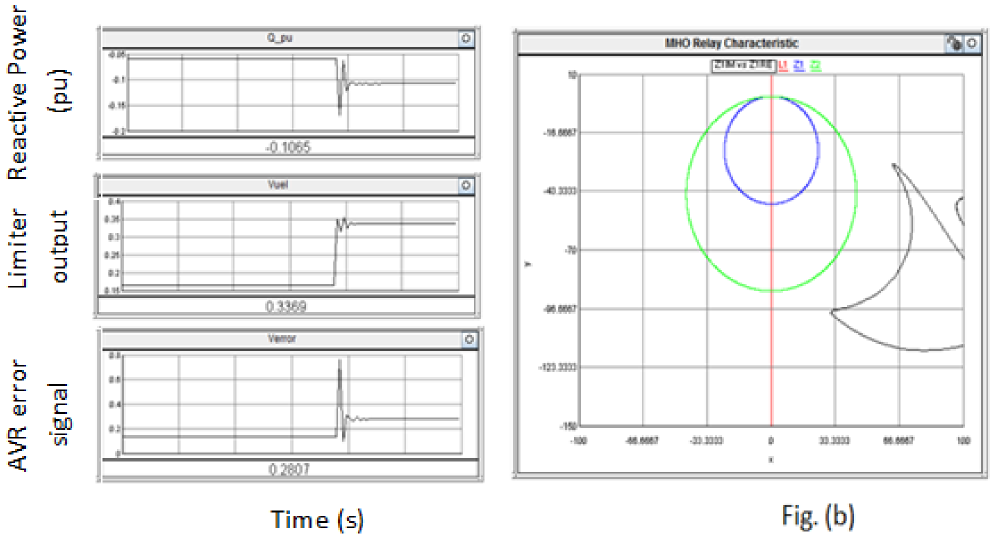

Fig. (a)

Fig. (b)

Figure 6-22: Limiter operation at 50% excitation

Figure 6-23 shows other system parameters when the machine was excited by 50%. Although excitation had been reduced, the limiter was able to ensure that the system remains in stable operation

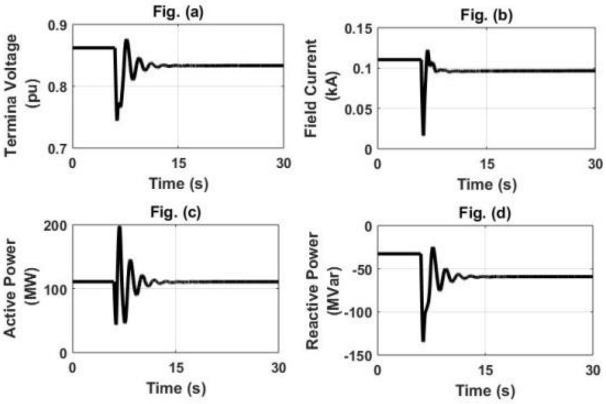

Figure 6-23: System parameters at 50% excitation

Case 2 involves testing coordination between field failure and undervoltage protection. Based on the settings in the relay, the field failure relay should always operate during underexcitation condition and the undervoltage is dependent on field failure. Figure 6-24 illustrates the field failure relay operation through MHO characteristic. Both zones are detected when the limiter could not operate to boost the system excitation.

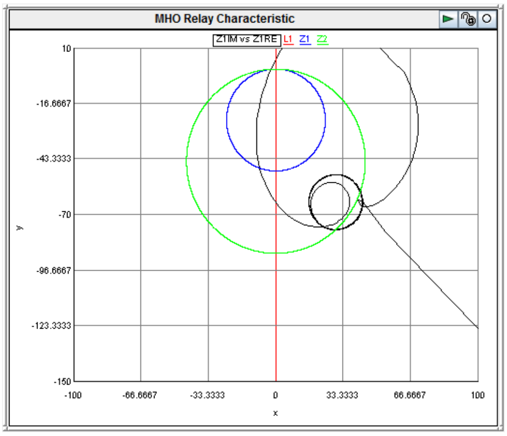

Figure 6-24: MHO relay operation

Figure 6-25 illustrates the limiter action at low excitation levels; this condition is practically showing the limiter failing to operate allowing system backup protection operation.

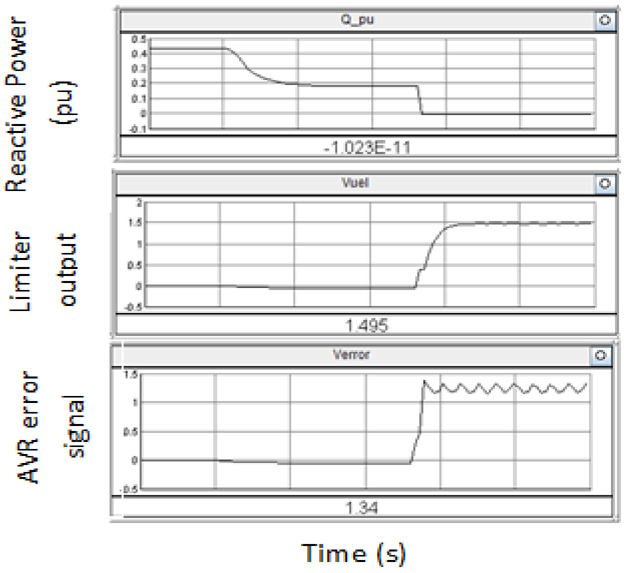

Figure 6-25: Limiter operation during field failure

Figure 6-26 shows the relay operation case study when both field failure and undervoltage conditions were detected simultaneously. This is achieved through relay operation settings and external control to simulate cases where both field failure and undervoltage relays operate at the same time and when field failure backups first before under voltage as shown in figure 6-26. The undervoltage detection in figure 6-26 is primarily due to field failure. When the field excitation reduces, the machine terminal voltage reduces due to the loss of field and the undervoltage relay operates.

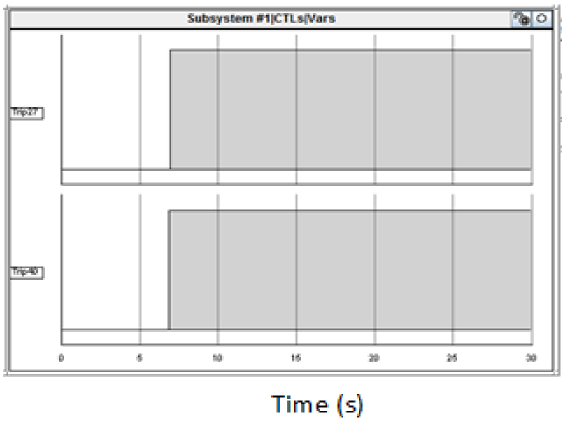

Figure 6-26: Field failure and undervoltage operating simultaneously

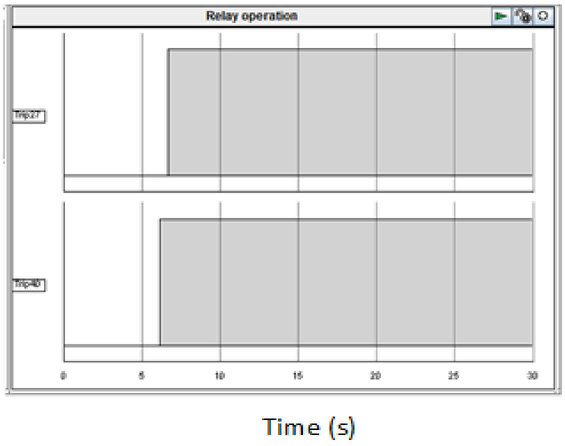

Figure 6-27: Field failure operation before undervoltage

Figure 6-27 shows the hardware relay signals confirming which elements have operated. Undervoltage is element 27 and 40 is for loss of field excitation. Both LED's show red light indication when the relay operated as indicated in figure 6-28.

Figure 6-28: Relay trip signals

The case studies conducted ensure adequate generator system protection during fault conditions. The sensitivity of the hardware relay is taken into consideration when conducting all the tests. Each excitation modeled is allowed to operate ensuring the machine is within its capability all the time, in cases where this does not happen, the backup protection system takes control by tripping the generator breaker isolating the system to prevent damages.

7. CHAPTER 7- Conclusion and Recommendations

This chapter summarizes the conclusion based on the work conducted in each chapter. Recommendations for future work are also entailed.

7.1. Conclusion

Case studies based on generator excitation control and coordination with respect to excitation limiters have been conducted and presented in this thesis. The generator protective functions studied are the ones closely coordinated with respect to excitation limiters and are employed to protect the generator. These include overexcitation (24), overvoltage (59), undervoltage (27) and loss of field excitation (40) protection elements. The studies conducted under different system contingencies employed both multifunction software generator relay and a commercial hardware generator protection relay. The results from the case studied are verified using both software and hardware relays. The results presented have shown the performance of each generator protection function solely as well as when coordinated with excitation limiters.

Generator excitation control and excitation limiters mainly require specific techniques to enable control and protection studies. In this thesis, a phase domain synchronous machine model has been utilized, this type of a generator model enables modeling of external excitation control systems which makes it easier to conduct excitation system control studies and protection coordination. The motive behind these studies is that normally the operation of generators is easily affected by internal faults as opposed to external disturbances and therefore require adequate control and protection schemes to ensure that the machine operates within its capability and if not; protection takes over to prevent damages.

A thorough research has been conducted on different literatures related to the dissertation. The methodologies and techniques presented by different authors have been reviewed and summarised according to relevancy. Most literatures based on excitation system control and protection studies have shown that excitation limiters may be modelled differently, based on the capacity of the machine being used as well as studies conducted by different users. However, it has also been concluded that irrespective of different modelling of the excitation limiters, the operation remains the same. The thesis focus is more on the operation of overexcitation and underexcitation limiters when coordinated with their respective protection elements. In the overexcitation region, the overexcitation limiters are coordinated with over excitation (24) and over voltage (59) protection whereas underexcitation operation is coordinated with loss of field (40) and undervoltage (27) protection. The theory of operation of each generator protective function had to be considered carefully for both software and hardware studies.

The relay settings applied when using both relays were carefully studied to ensure there is no misoperation and to ensure that each configuration is adequate. The relay setting calculation and modelling of excitation limiters were based on IEEE standards for ac generators.

Real time digital simulator has been utilized for all the case studies conducted with the aid of RSCAD software simulation tool. Step wise procedures have been followed in conducting and testing the models. Each step has been followed carefully as different case studies were conducted. The excitation limiters modeled and tested include straight-line characteristic under-excitation limiter and two overexcitation limiters. These limiters were simulated in the underexcitation and overexcitation region respectively. Also, during coordination studies, each limiter had to be tested to ensure proper operation before any fault condition was implemented. The results demonstrated confirm theoretical aspects based on different literatures reviewed as well as methodologies employed in testing excitation limiters with protection of generators for coordination. During the implementation of protection coordination in the underexcited region, loss of field and undervoltage protective functions were employed. Undervoltage function in some literatures is not used because it normally causes false tripping of the relay; this was prevented by modeling external control circuit which ensured that the undervoltage element operates only during undervoltage conditions.

Hardware in-loop testing and verification using a commercial relay has been performed. The simulation case studies done using SEL 300-G is similar to the ones conducted using the software relay. However, in some cases certain adjustments in protection settings were done so as to allow the operation of excitation limiters before its respective protective function. From the set of results obtained from both software and hardware, it has been shown that excitation limiters do not trip the machine but are employed to prevent the generator from operating in zones that are thermally dangerous to the machine. When a major disturbance occurs in a power system, it is expected that generators operate to return the system to a stable condition and to achieve this; generators must remain synchronized and be operated within their capability limits. This has encouraged the coordination of generator protection with generator excitation control studies conducted in the dissertation.

7.2. Recommendations for future work

The work performed and presented in this dissertation confirms the theories from the literatures. It is however also important to know that the work conducted based on excitation systems is not only limited to the scope presented in this thesis. Therefore it is of great importance to recommend certain studies which could be conducted using the same system network. These include but not limited to the following:

- When conducting studies including underexcitation limiters, it is important to know and determine the purpose of the limiter in service as these can vary from solving stability problems, heating or protection co-ordination. In this way, it is easier to know the expectations from the studies as well as evaluating the dynamic performance of the limiter. In this thesis, the limiter employed mainly considered stability and protection coordination.
- Three models for UEL are developed, each using different set of input in their model. The straight-line characteristic model have been used for the simulation case studies conducted, however, it is always recommended to test each limiter characteristic. Although the operation of each limiter is the same; conducting same studies with all three types is encouraged as this would help compare how each limiter operates under different scenarios.
- It is important to evaluate the interaction of excitation limiters with other controls, for instance in attempt to achieve proper protection coordination, the UEL could be highly responsive elevating the voltage levels in the system, this could lead to stability problems or in rare cases the system could be forced to operate in the overexcited region, and if the control for this region is not employed, the system could be in danger.
- Following similar hardware-in-loop testing procedures, it should be possible to conduct studies using different generator commercial relays to see how each relay operates under the same system contingencies and to compare the operation of each relay.

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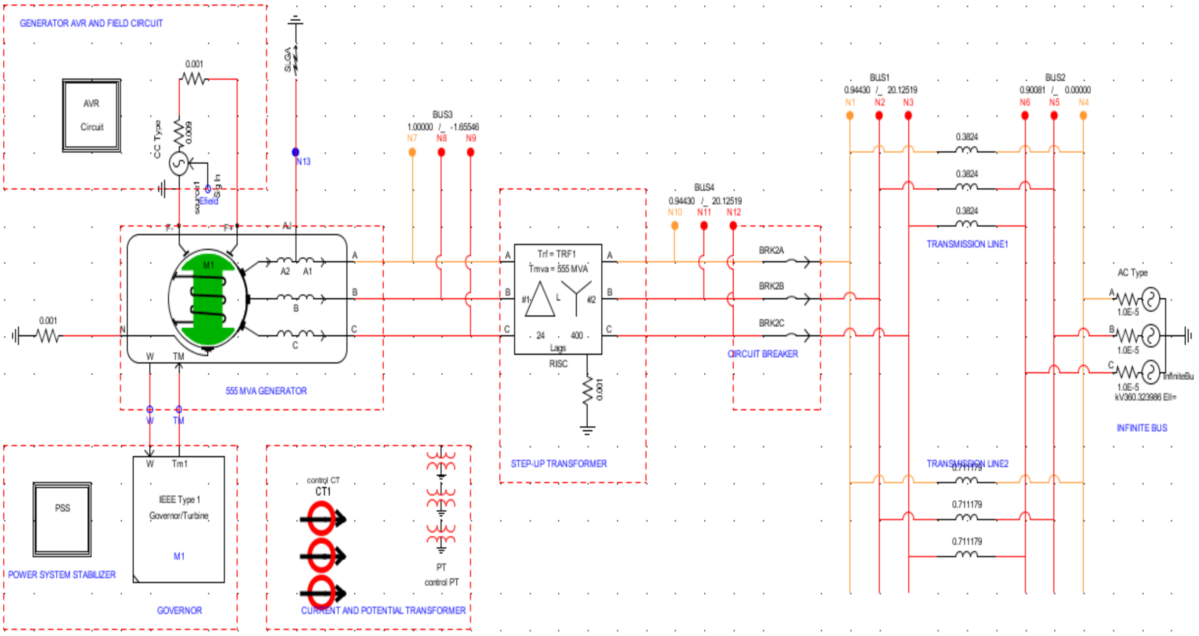
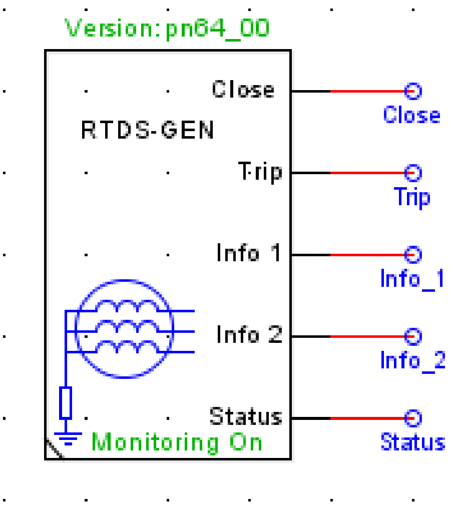
APPENDIX A

A. System model on RSCAD



B. Generator software relay



Appendix B

C. Generator model Parameters

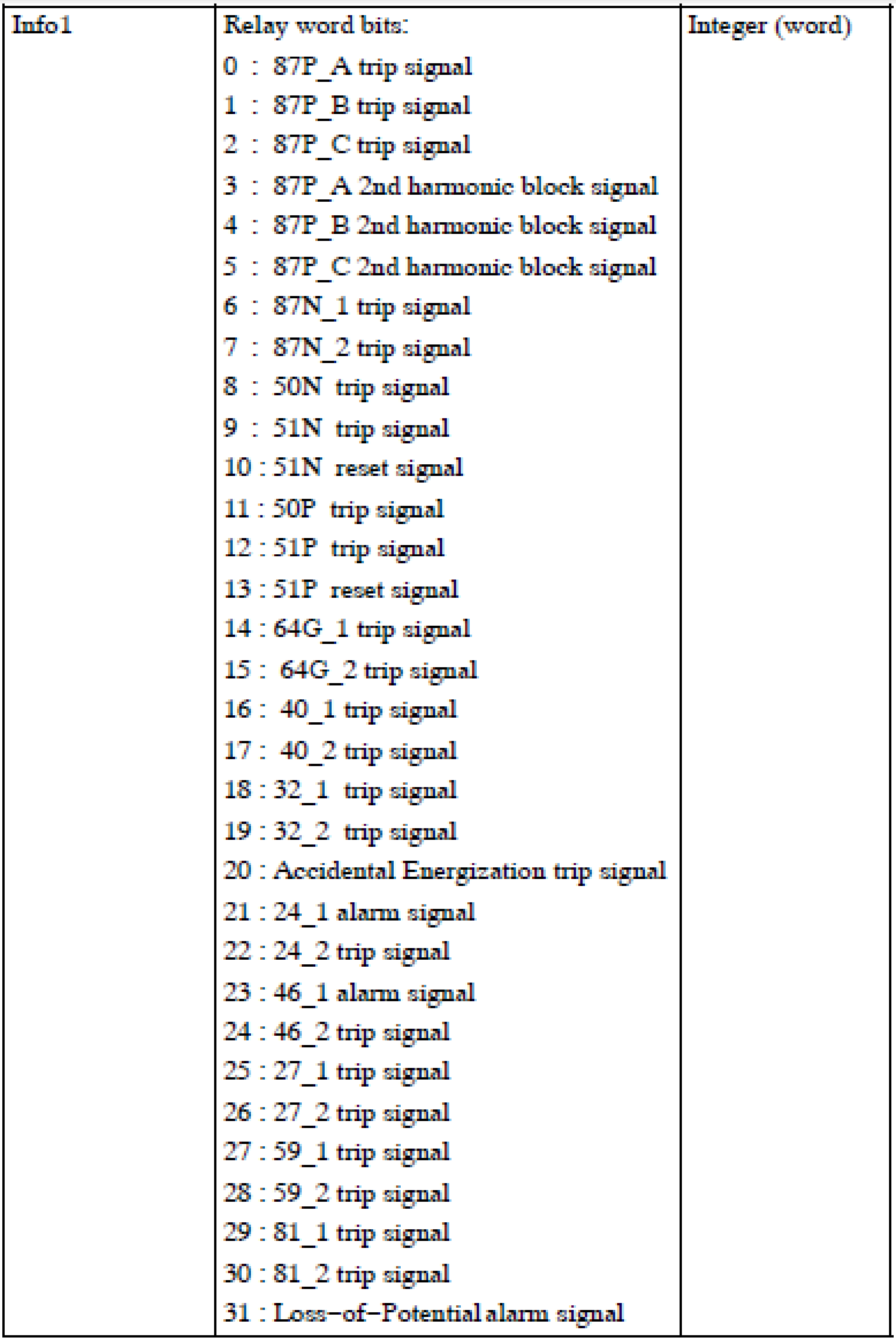
GENERATOR PARAMETERS	
MVA Rating of the machine	**555 MVA**
Line to line voltage	**24 kV**
Frequency	**60Hz**

Reactance values

x_d	**1.81**	x_q	**1.76**	x'_d	**0.3**	x'_q	**0.65**
x''_d	**0.23**	x''_q	**0.25**	x_l	**0.15**	R_a	**0.003**
T'_{d0}	**8s**	T'_{q0}	**1.0s**	T''_{d0}	**0.032**	T''_{q0}	**0.047s**
H	**3.5**	K_D	**0**				

Appendix C

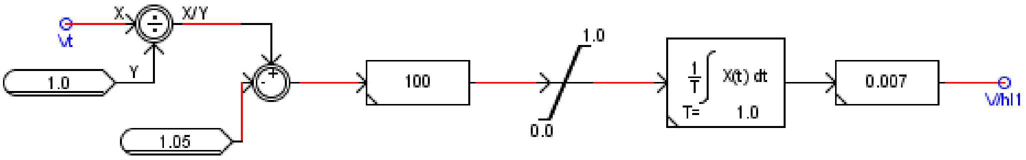
D. Relay bit trip signals



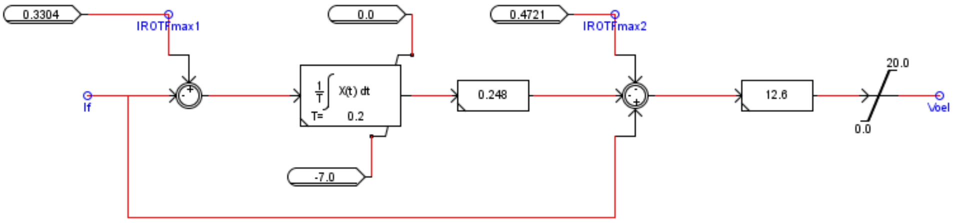
Info1	Relay word bits: 0 : 87P_A trip signal 1 : 87P_B trip signal 2 : 87P_C trip signal 3 : 87P_A 2nd harmonic block signal 4 : 87P_B 2nd harmonic block signal 5 : 87P_C 2nd harmonic block signal 6 : 87N_1 trip signal 7 : 87N_2 trip signal 8 : 50N trip signal 9 : 51N trip signal 10 : 51N reset signal 11 : 50P trip signal 12 : 51P trip signal 13 : 51P reset signal 14 : 64G_1 trip signal 15 : 64G_2 trip signal 16 : 40_1 trip signal 17 : 40_2 trip signal 18 : 32_1 trip signal 19 : 32_2 trip signal 20 : Accidental Energization trip signal 21 : 24_1 alarm signal 22 : 24_2 trip signal 23 : 46_1 alarm signal 24 : 46_2 trip signal 25 : 27_1 trip signal 26 : 27_2 trip signal 27 : 59_1 trip signal 28 : 59_2 trip signal 29 : 81_1 trip signal 30 : 81_2 trip signal 31 : Loss–of–Potential alarm signal	Integer (word)

Appendix D

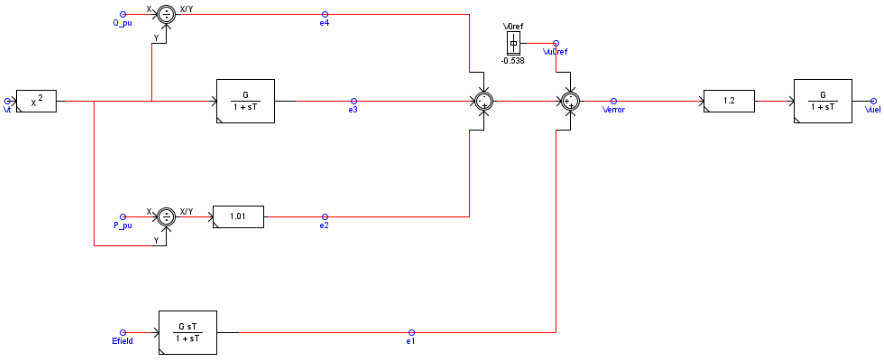
E. V/Hz excitation limiter



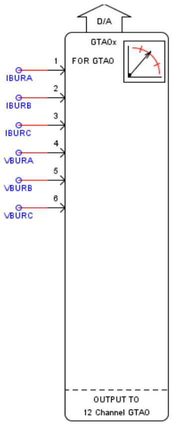
F. OEL excitation limiter

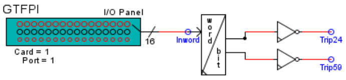


G. Underexcitation limiter



H. GTAO card for HIL





I. Commercial relay testing for individual protective elements

a) Overexcitation (24)

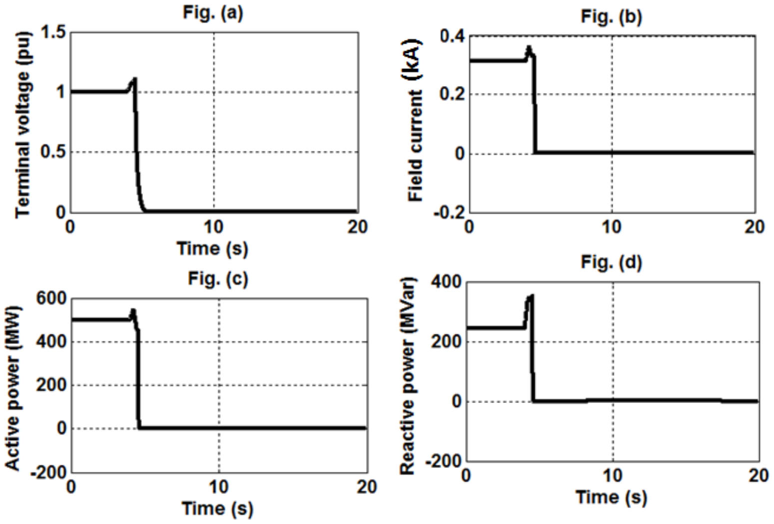


Figure 0-1: Over-excitation level 1

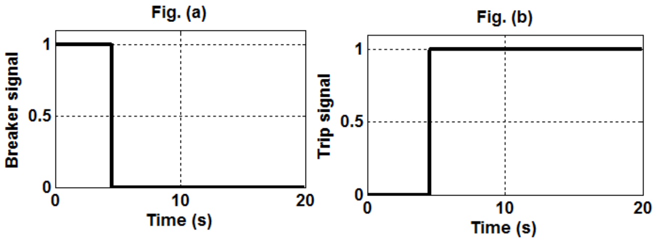


Figure 0-2: Relay operation for level 1 overexcitation

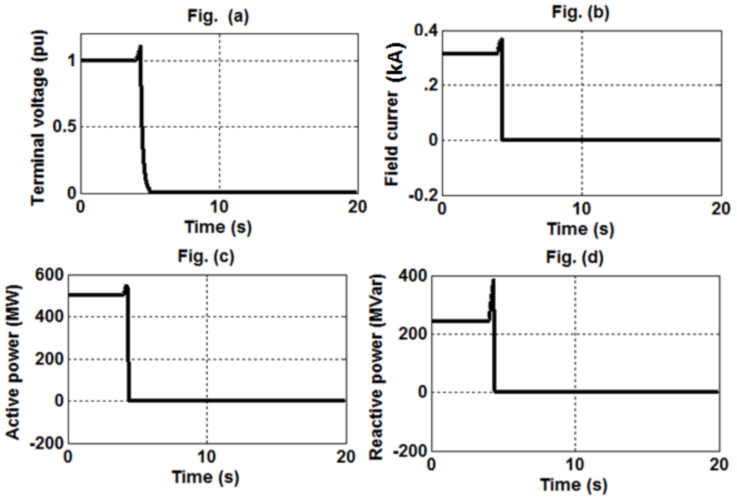


Figure 0-3: System parameters at level 2 overexcitation

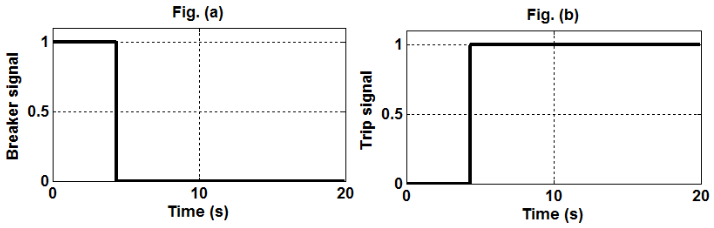


Figure 0-4: Relay operation at level 2 overexcitation

Figure 0-5: 24 element operation

b) Over-voltage (59)

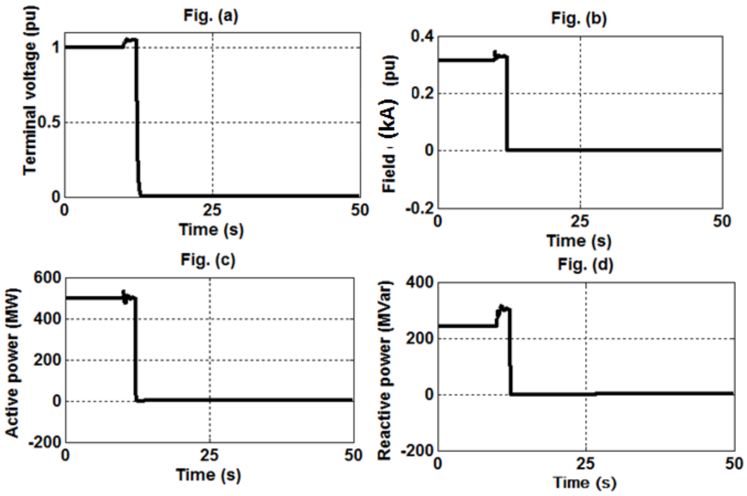


Figure 0-6: System parameters for level 1 over-voltage

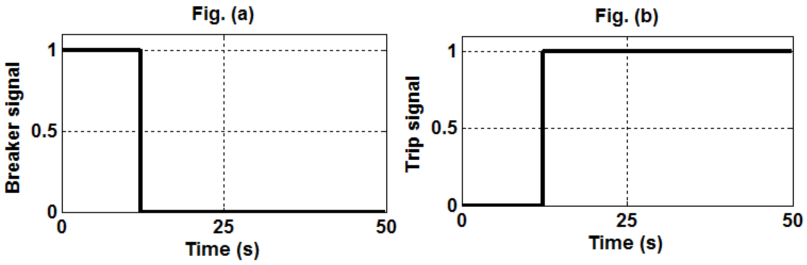


Figure 0-7: Relay operation for overvoltage level 1

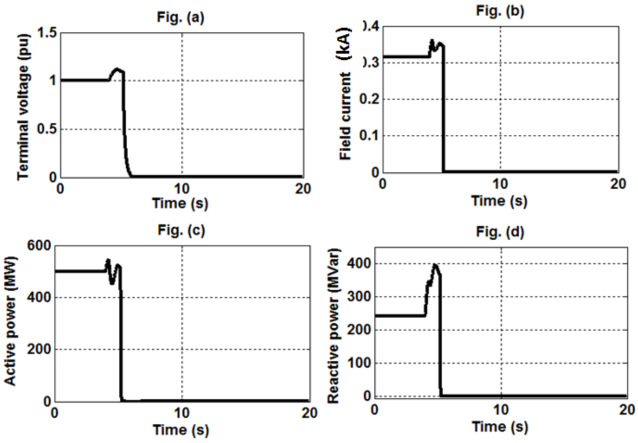


Figure 0-8: System parameters for overvoltage level 2

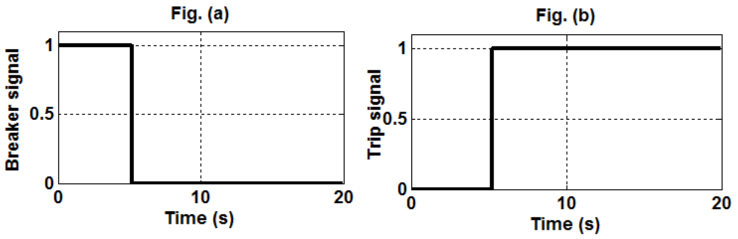


Figure 0-9: Relay operation for level 2 overvoltage

Figure 0-10: 59 element operation

c) Under-voltage (27)

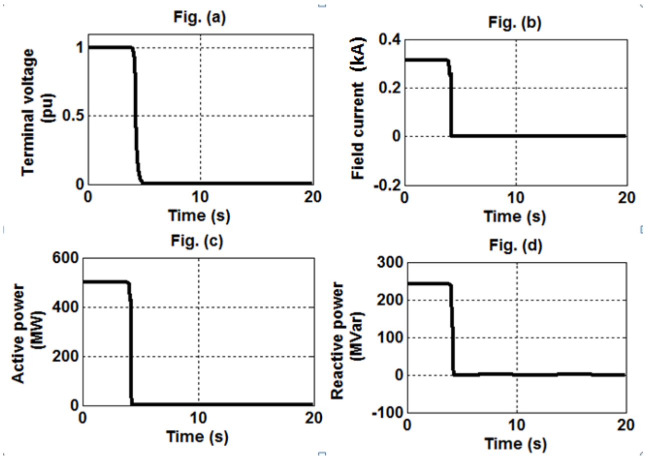


Figure 0-11: System parameters for level 1 undervoltage

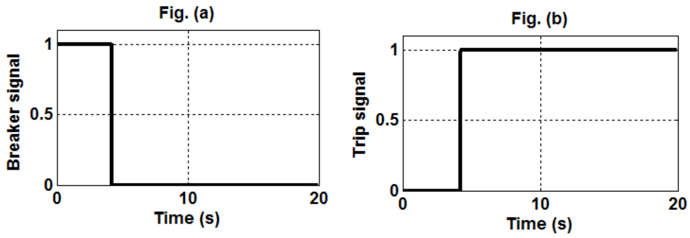


Figure 0-12: Relay operation for level 1 undervoltage

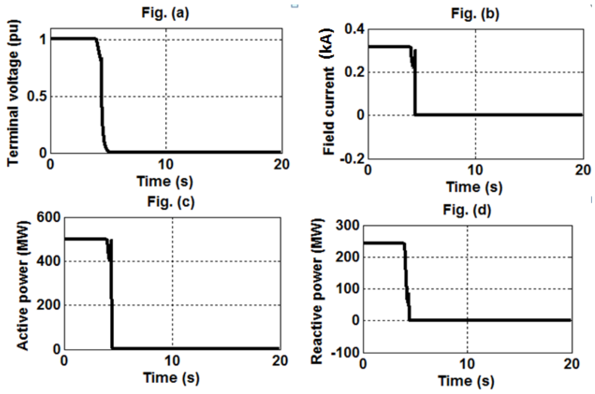


Figure 0-13: System parameters for level 2 undervoltage

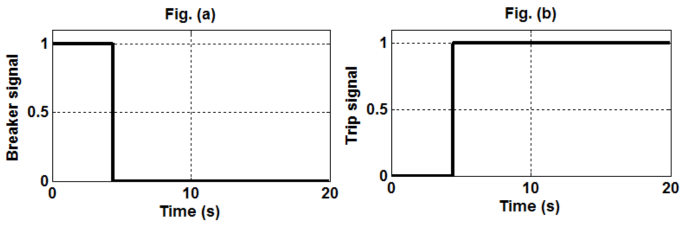


Figure 0-14: Relay operation for level 2 undervoltage

Figure 0-15: 27 element operation

d) Loss of field excitation (40)

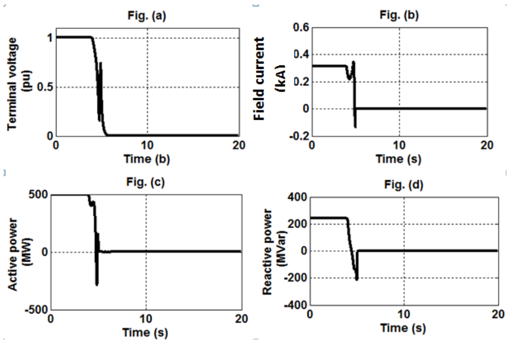


Figure 0-16: System parameters for level 1 field failure

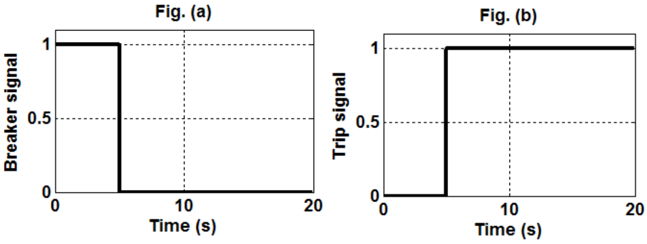


Figure 0-17: Relay operation for level 1 field failure

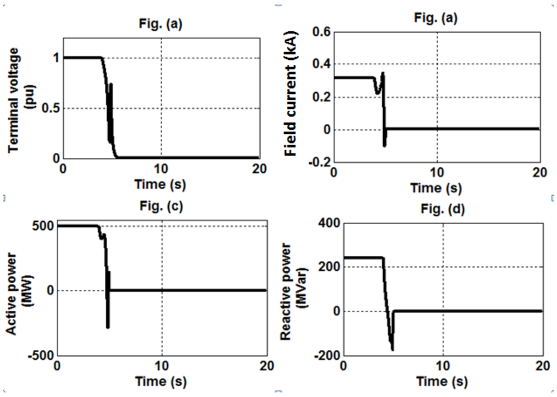


Figure 0-18: System parameters for level 2 field failure

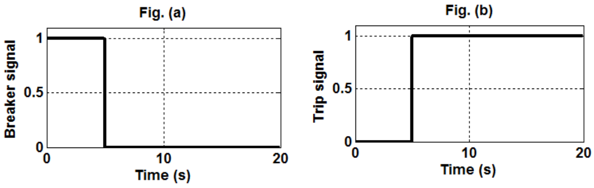


Figure 0-19: Relay operation for level 2 field failure

Figure 0-20: 40 element operation