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CONTINGENCY ANALYSIS OF POWER SYSTEMS IN PRESENCE OF GEOMAGNETICALLY INDUCED CURRENTS

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CONTINGENCY ANALYSIS OF POWER SYSTEMS IN PRESENCE OF GEOMAGNETICALLY INDUCED CURRENTS

THESIS

A thesis submitted in the partial fulfillment of the requirements for the degree of Masters of Science in Electrical Engineering in the College of Engineering at the University of Kentucky.

By

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ABSTRACT

CONTINGENCY ANALYSIS OF POWER SYSTEMS IN PRESENCE OF GEOMAGNETICALLY INDUCED CURRENTS

Geomagnetically induced currents (GIC) are manifestations of space weather phenomena on the electric power grid. Although not a new phenomenon, they assume great importance in wake of the present, ever expanding power grids. This thesis discusses the cause of GICs, methodology of modeling them into the power system and the ramifications of their presence in the bulk power system. GIC is treated at a micro level considering its effects on the power system assets like Transformers and also at a macro level with respect to issues like Voltage instability. In illustration, several simulations are made on a transformer & the standard IEEE 14 bus system to reproduce the effect of a geomagnetic storm on a power grid. Various software tools like PowerWorld Simulator, SimPower Systems have been utilized in performing these simulations. Contingency analysis involving the weakest elements in the system has been performed to evaluate the impact of their loss on the system. Test results are laid out and discussed in detail to convey the consequences of a geomagnetic phenomenon on the power grid in a holistic manner.

Keywords: Geomagnetically Induced Currents, PowerWorld simulator, IEEE 14 bus system, Voltage instability, Contingency Analysis.

Sivarama Karthik Vijapurapu.
CONTINGENCY ANALYSIS OF POWER SYSTEMS IN PRESENCE OF GEOMAGNETICALLY INDUCED CURRENTS

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Date: 7/24/12
Dedication

“If I have seen further it is by standing on ye sholders of Giants.”—Sir Isaac Newton

To my grandfather Ramadas Vijapurapu, for exemplifying the man I strive to become.

To my grandmother Venku Bai Vijapurapu, a shining gem in the shadows, for her perpetual affection, warmth and encouragement.

To Sri Lakshmi Bai, for everything she said, did and is for me.

To my parents, Narayana Rao and Swarana Latha Vijapurapu, for I owe my all to them. Their confidence in me supersedes my own.

I stand overwhelmed by all your love and reciprocate it humbly thorough this work as a token of my gratitude.

Sivarama Karthik Vijapurapu

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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

Owing to the escalating demand for electricity and the inclusion of renewable energy resources in remote locations into the energy portfolio, power grids in the US and around the world have witnessed an enormous increase in the span of area they encompass. With the expanding power grid and the need for continual supply of electricity, reliability is of paramount importance. Any unforeseen disturbance in the usual functioning of the grid can have very far reaching consequences if necessary contingency measures are not put in place. Large scale disruptions of the power grid not only cause stress in the tightly knit power system but also voltage instability, un-coordinated load shedding, damage, loss or erratic operation of power system assets propelling it towards collapse and system blackout. Advent of marketing strategies like deregulation of electricity rates has also increased the need for incessant supply of power to the end users who are sensitive to outages [1].

Although the power grid is robust and impervious to most disturbances, its vulnerability cannot be ruled out as power systems nowadays tend to be operated near their respective operating limits owing to increasing demand from industries, communications and for general domestic usage. This situation arises due to growing economic and environmental concerns in building new power transmission systems to harness energy sources located in spatially distant areas.
Expansion in the span of the power systems make them come into contact with several factors that have been previously unidentified or neglected altogether and can considerably affect the normal operation of the grid. Apart from transmission line faults and equipment failures which generally cause disruptions in the power grid, weather conditions are also an important factor during system planning and design. Although terrestrial weather is taken into consideration by planners and system designers, space weather is an issue that is becoming increasingly important.

Space weather is defined as a consequence of the interaction between the Sun, the Earth’s magnetic field and the atmosphere [2]. It is mainly driven by the activity in the Sun and its effect on the earth. Any significant variation in the space weather causes a corresponding Geomagnetic Disturbance (GMD). A GMD is defined as a temporary perturbation in the earth’s magnetosphere caused by solar phenomenon such as Solar flares, Coronal Mass Ejections (CME) approaching towards the earth from the sun. NERC’s Interim Reliability Assessment Report [2] attributes this solar activity due to the reactions taking place inside the Sun. Space weather phenomena such as Solar Flares, Radiation Storms and Geomagnetic storms are three acknowledged solar activities directed towards the earth.

Of the above three phenomena, Geomagnetic storms were observed to have the most adverse effect on the power systems. A Geomagnetic storm is caused by the rapid influx of Coronal Mass Ejections (CME) comprised of electrically charged particles and strong magnetic fields from the Sun directed toward the upper layers of the earth’s atmosphere.
These electrically charged particles create a stream of current called Electrojets in the atmosphere. Beams of these particles hurling towards the earth collide with the constituents of the earth’s ionosphere and produce fluorescence commonly known as Aurora.

![Graphical Description of a Coronal Mass Ejection](image)

*Figure 1.1 Graphical Description of a Coronal Mass Ejection [2].*

Substantial alterations in the intensity and direction of these electrojet currents can induce ground-based voltage (potential) differentials between locations spatially apart. These ground potential differences can cause currents to flow through the grounded connections of transmission lines and transformers if the resistivity of the ground to a sizable depth is greater than the resistivity of the transmission or transformer. This event occurs more often in greater degree in areas that sit atop igneous rocks [3]. These currents induce a potential on the earth called Earth Surface Potential (ESP).
The effect of this ESP is prominent between the grounded points of the AC power system giving rise to flowing currents. The sequence of events described above drives the quasi-dc current through one grounded point of the system into another. Fig 1.2 illustrates the entire phenomenon.

![Figure 1.2 Geomagnetic effects on electric power grids [4]](image)

Manifestation of all these solar and geological reactions can be seen as fluctuations in the magnetosphere of the earth giving rise to quasi–dc stray currents called Geomagnetically Induced currents (GIC) abbreviated henceforth as GIC in the power system. GICs have adverse effects on conductive equipment such as Power grids, Transmission lines, Underground pipelines and Telecommunications cables.
Critical space and terrestrial infrastructure can suffer damage during the course of a CME. In the past, communication satellites have observed disruptions in their operations during the course of a geomagnetic event. Of all the conducting equipment, Electric Power Transmission Networks faces the greatest threat from GIC as they have a vast footprint which makes them better receptive to stray GIC currents. As susceptibility to GIC increases, the grid becomes overloaded leading to subsequent problems like voltage fluctuations and widespread power outages due to equipment failure [5].

Interdependence of Industrial, Communications and other infrastructural sectors require power as a basic necessity for their function. Hence, a disruption of Power over a long period of time spanning a large area can have globally resounding consequences in terms of economic losses incurred. Needless to say, the damage caused to public and emergency infrastructure due to a power blackout [6].

In most natural disasters, the less developed areas suffer the biggest impacts. Ironically, during a geomagnetic storm, the sophisticated power grids that couple so well to the space environment is that which makes highly developed areas with more power needs bear its brunt.
1.2 MOTIVATION

The prime motivation of this thesis was the significant impact an organized strategy could make in dealing with GIC over a very large power grid. In doing so, several valuable power system assets can be shielded from the hazardous effects of GIC thereby saving a lot of time and money in having to replace them.

There exists no universal or single preventive measure for GIC because geomagnetic storms vary in direction and intensity through space and along the spatial location of the power system. Geomagnetic storms were initially thought of being restricted to higher latitude regions near the poles, but during recent events, GICs were observed to have effect as far as countries like South Africa. Hence, a multi-faceted, tactical and layered approach is required. This includes equipment hardening to GIC and augmenting system operations evolving into a suitable contingency plan. GIC being a phenomenon having a continental footprint, mitigation measures differ from case-to-case basis, as do the impacts on the power system in different areas.

Developing a unique mitigation measure for GIC is particularly difficult because not much data exists from previous storms when space monitoring and GIC monitoring devices were not in vogue. Thus, an in-depth analysis and integration of GICs is to be undertaken to observe the impacts.

Modeling GICs into the system is an important step in studying its effects so that system operators can take educated, real-time decisions in countering the flow of GIC.
Operational measures in terms of protecting system assets, maintaining voltage stability, variable system configurations are essential in arresting the effects produced by GICs.

The thesis focuses on modeling GICs into the power system, observing the effects on the power system assets, identify vulnerable areas and develop an organized strategy to mitigate GIC. Due to the hazardous effects of GIC, this kind of an approach is an important step in assessing the dangers posed to the system holistically so that power system operators can make educated decisions when countered by a GMD.

By identifying the vulnerable points and observing the impact of a GIC on them, a valuable insight can be developed which can help in design of power system equipment that can withstand the effect of a GMD, and also aids professionals while planning the system.

The thesis drew its initial motivation from [7] in which a software tool was used to simulate the effects of GIC on a power network. The thesis uses the tool to simulate the scenario of a geomagnetic storm with as little input as possible and observe the deviation of the grid from its stable operating point. Building on the observations made, the problems posed to the grid by the disturbance are identified.

Basing on the existing guide lines set by utilities during natural disasters, best system practices are developed for geomagnetic terms in terms of a systematic schedule addressing each issue posed by GIC flows in the system. This is possible only after analyzing the system in detail which this thesis hopes to accomplish.
1.3 OUTLINE

The first chapter prefaces background information about space weather phenomena leading to a geomagnetic storm and introduces several prerequisite terms in understanding the underlying sequence of events that cause this activity. Consequences of such an event on the present day bulk power system are inferred and the necessity to broach the issue is outlined.

The second chapter details several previous occurrences of a geomagnetic storm and their associated effects such as GIC on the power systems in various countries. This is intended to elucidate and establish the risks and hazards posed in the aftermath of a geomagnetic disturbance. Based on this knowledge, the effects are explained illatively and foundations are laid to discuss them in specific in the following chapters.

The third chapter discusses the various methods in modeling the circulating GIC currents into the power system. GIC calculation tool in PowerWorld Simulator used in this thesis is suggested and explained elaborately. The IEEE 14 bus system is used as a test case to explain GIC calculation and it is again revisited in the fifth chapter while addressing voltage stability.

The fourth chapter constitutes the observed effects of GIC on transformers in a comprehensive manner. Several aspects such as saturation characteristics, current harmonics, variation in power statistics and thermal degradation are hashed out and substantiated by a series of simulations performed using SimPower systems toolbox in Simulink.
The fifth chapter broaches the subject of Voltage Stability. A technique called Modal analysis is utilized in determining steadiness of the system voltage levels in presence of GIC. A MATLAB program is developed to observe the voltage stability of the system. The GIC calculation tool introduced previously is used to subject the IEEE 14 bus test case to several operating points and to observe its stability at each instance.

The sixth chapter comprises of numerical and pictorial results of various simulations undertaken in the preceding chapters. These results are discussed and several inferences are made which validate the hypothesis discussed earlier.

The seventh chapter concludes the entire research work in this thesis. The results obtained are laid down along with some useful recommendations. In addition, scope for future work and possible extension pertaining to the content discussed in this thesis is briefly stated.
CHAPTER 2: LITERATURE REVIEW

This chapter comprises a brief account of previous occurrences of geomagnetic storms & their associated effects on the bulk power system around the world. The section 2.2 takes a closer look at the effects of a GIC storm on power system assets.

2.1 HISTORY OF GEOMAGNETIC STORMS & GIC

In order to completely understand the disturbances caused by a GMD to the power grid, it is necessary to be cognizant of previous instances of such occurrences. Geomagnetic storms coincide by the reactions occurring in the core of the sun. The main threat that a Geomagnetic storm poses to the Power grid are the circulating low frequency currents called Geomagnetically induced currents(GIC) that are generated as a result of a GMD event owing to the conductive nature of the earth. These currents enter and exit the discretely earthed power grid at several points affecting the operation of the grid significantly. GICs have been observed to cause several problems like harmonic loading and tripping of reactive power elements and transformer saturation thereby creating a cascading effect possibly leading to voltage collapse and load blackout of the entire grid.

There have been several instances of GICs disrupting the power network, the most recent being the GMD storm that caused the collapse of the Hydro-Quebec system in Canada in March 1989. Even though, such phenomenon is termed as a low frequency event i.e., the possibility of such an event occurring being meager, it is a high impact event due to the scope of the area it encompasses [8].
a. 1859 Carrington Event

The geomagnetic storm that occurred in 1859 was the first identified such event in modern times. The storm was characterized by an intense flare associated with auroras visible as far as South Panama and the Caribbean. Since the bulk power system was not in existence, the effect of the storm was seen in the telegraphic system that was extensively used at that time. Several telegraph stations in Europe and North America experienced disturbances during transmission owing to strong magnetic field being induced from the earth. Later statistics have shown that it was the largest geomagnetic storm to have been recorded and several researchers have opined that if such a storm was experienced today, the consequences would be have been disastrous [2].

b. 1989 Geomagnetic “Super Storm”.

The Geomagnetic storm that struck the Hydro One Quebec transmission system in Canada was in many ways a landmark event in terms of the research that was carried out after the event, in protecting electric grids from geomagnetic storms. On March 10th 1989, astronomers observed an unprecedented discharge of electrically charged solar material towards the earth. The effects of this event were felt three days later on March 13th when due to the rapidly changing magnetic field exerted by the earth gave rise to ground currents called GICs in the 9500 MW,745 KV Hydro One transmission system in the Quebec province in Canada. On account of the igneous, low conductive nature of the ground the transmission system sat on, these currents entered the system through the grounded neutrals of the transformers.
Due to the low frequency of GICs, the transformers were driven into the saturation region of their causing half cycle saturation resulting in harmonics in the output. Apart from the harmonics generated, GICs have also been observed to cause increased Reactive Power consumption by transformers, heating and charring of windings due to the leakage of magnetic flux. The interesting thing to note is that equipment damage was mainly caused due to uncoordinated load shedding and system separation leading to temporary voltages. The storm caused the blackout of 745 KV transmission system due to the generation Geomagnetically induced currents(GIC) which caused the harmonic overloading of 7 Static VAR Compensators(SVC) which were essential in maintaining the voltage stability of the system. Owing to the high harmonic content in the currents, the protection systems tripped several long distance transmission lines and reactive power elements leading to voltage collapse of the system. The storm which took 92 seconds to cause this province wide blackout ultimately left 6 million of customers without power for 9 hours [2].

c. 2003 Halloween Storm

The GMD events that occurred during October 29-September 2 were termed as the Halloween storms. This GMD was particularly distinct characterized by a number of solar flares spread over several days causing high levels of GIC to be detected in several transformer units in several countries in Europe. Disturbances were detected in the British Isles [9] and the Scottish Power Network [10] during the storm.
In Sweden, this storm knocked out power in the HV transmission system in Malmo in the Southern province leaving about 50,000 customers in the dark for about 1 hour. An unprecedented high value of transformer GIC neutral current of 330 A was observed during this event leading to its failure [11].

Early researchers opined that Geomagnetic storm is a problem that is only relevant to HV power systems in countries which are situated in high latitude regions near the poles. Contrary to this notion, GICs were observed in several mid latitude countries such as South Africa [12], Spain [13] and New Zealand [14].

The locational significance but latitudinal independence was brought to the front by the effects of GIC in countries which are geographically disparate. Observations in several countries once again emphasize the continental footprint of a geomagnetic storm.

It is to be noted that the incidents mentioned are only a few among the many number of disturbances that have been caused by GICs. A detailed list of damage caused by GICs is referenced at the end of this thesis.
2.2 EFFECTS OF GIC ON THE BULK POWER SYSTEM

The effects of GIC on the bulk power system can be described as accretive with time. Being currents with frequency as low as 0.01 Hz, they can be regarded as dc currents with respect to the traditional 60 Hz ac power system. Being aberrant currents in the power network, they spawn several disturbances which are cumulative and lead to several other problems. GICs can be characterized by power system configuration, earth features and the storm parameters.

Since the entry point of GICs is through the grounded neutrals of the transformer, they are the most affected equipment during a geomagnetic disturbance. During a geomagnetic disturbance, transformers are driven to saturation region of their operating curve which is described as half cycle saturation.

*Figure 2.1 Illustration of GIC entry into the power system*

Since the entry point of GICs is through the grounded neutrals of the transformer, they are the most affected equipment during a geomagnetic disturbance. During a geomagnetic disturbance, transformers are driven to saturation region of their operating curve which is described as half cycle saturation.
Half cycle saturation causes several other problems like increase in reactive power consumption in the windings which is a power loss, heating up of windings due to leakage of magnetic flux, high harmonic content in phase currents. Recurrence of this phenomenon over several cycles leads to deformation of transformer windings, decrement of equipment lifetime and increased vulnerability to other disturbances. Normally, a few amperes of current is enough to disrupt transformer but currents over hundreds of amperes were detected in the ground neutrals of transformers in affected areas previously in countries like Finland [25]. A separate chapter has been dedicated to observe the effect of GIC on transformers in due course of this thesis.

Apart from internal damage to transformers, flow of these stray currents cause harmonic propagation into the transmission lines causing power losses and disruption of other power system assets like capacitor banks and protection/control systems [26] which are susceptible to any unusual current flow in the system.

Figure 2.2 GIC Effects on Power Systems
Owing to the loss of Reactive power and capacitor bank tripping due to harmonic overloading, the voltage stability of the grid is jeopardized leading to widespread outage and equipment damage. Also, drastic variations in Active and reactive Power flow may trip Transmission line operating at their limits. Unplanned power outage and load shedding will result causing huge losses to the industry and domestic sectors.

It has been observed that even low intensity GMD events can produce significant magnitude of GICs which can saturate the steel core of transformers. The prime example of this type of event is March 1989 blackout in Canada in which the entire Hydro-Quebec grid operation came to a standstill owing to saturation of transformers ensued by tripping of protection equipment leading to about 80% of grid blackout.

The general trend of increase in power demand every year and the lack of proper, local generation facilities will necessitate the transmission of power over long distances to keep up with the power needs. Continual growth of Load along with absence of necessary additional reactive power resources will cause reduced stability margins and also make it difficult to maintain a stable operating point.

Utility companies have to remain constantly vigilant by performing periodic vulnerability studies and developing mitigation mechanisms so that future real-time GIC assessment is possible.
This chapter talks about the different approaches that have been used before to model GICs into the power system. GIC modeling is an important step with regards to the protection of the bulk power system from the numerous hazards posed by it. GIC modeling is defined as a specific approach taken to reproduce the conditions that occur during a geomagnetic storm and calculation of the currents that evolve as a result of the variation of the earth’s magnetic field. Section 3.1 describes previous propositions put forward to quantitate GIC. The following section discusses the method that has been used in this method to model GIC into the bulk power system.

### 3.1 METHODS OF GIC MODELLING

In order to better understand and evaluate the grid response to GICs, modeling them into the predominantly AC system is an important step in characterizing their impact on the bulk power system. Quantifying GIC is a continuous travail for researchers because of the inherent non-linearity in the factors that induce GIC. Several factors have to be taken into consideration while modeling because of the vast nature of the grid.

GIC modeling can be broadly divided into two categories:

- Predictive Methods
- Analytical Methods
3.1.1 PREDICTIVE METHODS

Predictive methods make use of a certain quantity and its variation to correlate that with induced GICs using Neural Networks, Fuzzy Systems or several statistical analyses. Previously, using this approach, GICs were predicted by establishing a correlation between the temporal variation of ground induced magnetic field \( \frac{\partial B}{\partial t} \) using Artificial Neural Networks (ANN) by Lotz in [15].

On the same vein, forecasting Sunspot Numbers utilizing different ANNs which are then correlated to GICs in the system has been performed by Samin in [16].

A more localized approach was undertaken by Ngwira in [17] by investigating the properties of geomagnetic field, their time derivatives and locally recorded geomagnetic indices were used to correlate with observed GIC values in the past.

Similarly, Pirjola et al propose a multi layered ground conductivity model by defining new network coefficients to characterize GICs in the system in [17]. The results were then compared with those obtained by correlating GICs with locally observed geomagnetic field indices. Meager availability of data from magnetic observatories is a serious limitation to this approach.

Prediction of GICs was performed by determining the induced Geoelectric field using a technique called Complex Image Method (CIM) in [17]. The method although accurate does not directly calculate GIC but uses the induced electric field to predict them by assuming the earth to be a perfect conductor.
The ANN approach, although being useful in cases like GIC prediction where many non-linear relations exist, is highly specific as there is a difference in many important factors like ground conductivity, geographic location and system configuration from region to region. Another hurdle is the data set required to train such network due to the dearth of adequate GIC data in the network as GIC monitoring is a relatively new concept. Owing to these factors, the neural network approach in predicting GICs is highly localized to regions that usually experience or have experienced this phenomenon in the past.

Since GIC is a complex phenomenon and it being the final impact of a geomagnetic storm, physical modeling requires the induced Geoelectric field which causes the ESP to drive these stray dc currents into the power system. Determining them is beyond the scope of this thesis and is a topic of interest to a geophysicist rather than a utility engineer. Hence, GIC modeling can be divided into two independent steps-Geophysical step and Engineering step. The Geophysical step involves calculating the geo-electric field while the engineering step involves calculating GIC [18].

Thus, the above hindrances necessitate a more universal, adaptable technique in modeling GICs into the system involving network modeling.
3.1.2 ANALYTICAL METHODS

Analytical Methods can be characterized by the inclusion of the grid properties during GIC calculation. This approach is of more relevance to a utility engineer as it offers a focalized strategy in dealing with GIC hazards to the bulk power system.

It was observed that a geomagnetic storm causes a significant variation in the earth’s magnetic field. This varying magnetic field gives rise to an electric field termed as the “Geoelectric field”. Geoelectric fields precipitate potential differences between grounded points of the ac power system especially grounded wye neutrals of transformers. This potential difference is then used to calculate the GIC entering and exiting the system at grounded points.

Berge et al have envisioned a software simulator to map GIC into the power system by modeling the entire power system as an admittance matrix in [20]. A computing script known as GIC Simulator was developed in MATLAB to map the network components in a HV transmission system. Geographical co-ordinates are used to calculate the Voltage induced termed as ESP due to Geoelectric field. This voltage is then used as an input to the entire grid to calculate the GIC and to evaluate the grid response.

Another simplified method based on Singular valued Decomposition has been proposed by Trichtchenko et al in [21]. In this method, measured GIC values are included in the load flow equations of the grid which leads to an over determined system. The Least
Squares approximation method is then used to solve these equations so that accurate values of GIC currents can be calculated.

Similarly, Zou and Liu have proposed a GIC calculation software in [22] illustrated in Fig 3.1 based on a step wise algorithmic approach using a layered conductive model of the earth, the next algorithm for ESP calculation, and the ESP contribution to the network as a voltage source to calculate GIC.

Figure 3.1 Flow Chart of the Power Grid GIC Calculation Software
The main hurdle in modeling GICs into the grid using Analytical methods is that they are relevant for small systems containing a few buses. A typical power network maintained by a utility contains thousands of buses with huge number of network components and their respective grid values. Calculations involving all of these quantities are very tedious since GIC is a phenomenon having a large foot print. Thus, there is a need for an elaborate GIC mapping model that can include all the network components with their associated values, geographical co-ordinates so that the grid response is apprehensible to power system operators. Depending on the response of the grid, mitigation plans can be devised, tested and established.

This need was realized by several research institutes like EPRI which developed an open source software program called OpenDSS to evaluate the grid response to GICs. PowerWorld Corporation developed a tool in its simulator to calculate GIC values pertinent to the grid. This tool is extensively used in this thesis owing to its ease of operation, apprehensible GUI and in built data formulation. The following section discusses GIC calculations in PowerWorld using the GIC Calculation tool elaborately.
3.2 GIC MAPPING AND MODELING USING POWERWORLD SIMULATOR

PowerWorld Simulator is a power system simulation software capable of handling many a multitude of buses in a power grid. A specialized tool called Geomagnetically Induced Current Calculations was recently developed by Overbye et al in [7] to evaluate the risks posed by geomagnetic storms to the electric grid. Espousing the notion of power system vulnerability to time and spatial variations of dc voltages caused by GMD, this tool underlines the need for a focalized approach in evaluating GIC effects on power systems. By integrating this tool into the simulator, power system operators can observe real time changes in the power system with the entry of GICs into the grid.

Owing the vastness of the grid, it was felt to use as little as inputs as possible in assessing the risks due to GIC. Hence, apart from common power flow parameters, very few additional inputs were used in developing the tool. Substation parameters like grounding resistance, transformer coil resistances and their winding characteristics along with the geographical co-ordinates of each power system asset is required to facilitate GIC calculations. The simulations in the thesis make use of default values in the software.

As previously discussed, a dc voltage that is induced on the earth called the Earth Surface Potential (ESP) is used as the primary input into the system. This can be calculated by the GMD induced Electric fields that cause this voltage. These electric field values are readily available from weather monitoring services like the Space Weather Prediction Centre (SWPC) in USA and the Canadian Space Weather Forecast Centre (CSWFC) for Canada and the magnetic observatories associated with these corporations.
3.2.1 GIC CALCULATION TOOL

The GIC Calculation tool that is included in the simulation package was developed as an add-on feature. With a few additional inputs to the already existing system, GIC response can be easily evaluated. GIC is regarded to flow because of a potential difference between the earth and the substation ground neutral. Thus, substation parameters like Grounding Resistance, Transformer grounding resistance and their winding configurations are required for calculations.

There are two main strategies in evaluating the grid response using an input voltage. One is to consider the voltage as a dc voltage in the ground and the other as a voltage in series with the transmission lines [23]. Since the voltage is induced on the ground, it is but natural to take the first approach in modeling but as opined by Boteler and Pirjola in [24], the first approach has a limitation of being applicable for a uniformly induced electric field which is usually not the case in a real GMD event.

It is also possible to create a time varying GMD using an Electric Field (V/Km). Using this input, GMD induced transmission line voltages can be calculated which are depicted as the AC Line Input voltages tab in the figure. Such values can be generated on a time varying basis using different inputs of electric fields to simulate a continuous GMD event. The AC line Input voltages are calculated using the Electric Field and Geographical co-ordinates of the Substations.
Figure 3.2 GIC Analysis Form
According to [24], the induced dc voltage is the dot product of the electric field over the entire length of the transmission line.

\[ V_{\text{ind}} = E \cdot L = E_x L_x + E_y L_y \] \hspace{1cm} (3.1)

Where \( E \) and \( L \) are Electric Field (V/Km) and Length of the Transmission Line(Km) vectors respectively.

\( E_x \) = Northward Electric Field Component; \( L_x \) = Northward T_x Line distance.

\( E_y \) = Eastward electric Field Component; \( L_y \) = Northward T_x Line distance.

The induced transmission line voltage is the sum of the voltages calculated over small segments of the line.

The GIC Analysis form also contains other sub-pages like Areas, Buses, Generators, Lines and Substations which contain the system data of the grid. The Areas sub-page consists of the GIC MVar Loss field which is the sum of all GIC related Reactive power losses in the grid.

The calculations performed using this tool is directly integrated into the power flow of the entire grid using Include GIC in Power flow checkbox on the form. The Specified Time Point field is used to select the instance at which the GMD dc voltage values to be used in the GIC calculations. For simulative convenience, only the case of a uniformly induced electric field over the standard IEEE 14 bus system (Figure) has been studied in this thesis.
3.3 TEST SYSTEM DESCRIPTION

The IEEE 14 Bus system by American Electric Power (AEP) represents a small power system in Mid-Western USA. As seen from the Figure, only Buses 1 & 2 generate Active power ‘P’ with the former being the Swing bus in the system. Buses 3, 6 & 8 are the PV or Generator Buses in the system supplying Reactive power ‘Q’. The remaining Buses- 4, 5, 7, 9, 10, 11, 12, 13 & 14 represent the Load buses of the system. This system has been modeled using PowerWorld Simulator (Figure 3.4) for simulation purposes followed by the system data (Tables 3.1 and 3.2).

Figure 3.3 Single Line Diagram -IEEE 14 Bus System.
Figure 3.4 IEEE 14 Bus System in PowerWorld Simulator
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<tr>
<th>#</th>
<th>PU Volt</th>
<th>Θ</th>
<th>Load</th>
<th>Generation</th>
<th>G(MW)</th>
<th>B(MVar)</th>
<th>P.F</th>
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<td></td>
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* - Swing Bus, + -Generator (PV) Bus.
### Table 3.2 IEEE 14 Bus-Line Data

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<th>From Bus</th>
<th>To Bus</th>
<th>Device</th>
<th>R (p.u)</th>
<th>X (p.u)</th>
<th>B (p.u)</th>
<th>Tap Ratio</th>
<th>Loss</th>
<th>MW</th>
<th>MVar</th>
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<td>0.22304</td>
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### Table 3.3 Regulated Bus Data

<table>
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<tr>
<th>Bus Number</th>
<th>Voltage Magnitude (p.u)</th>
<th>Minimum MVar Capability</th>
<th>Maximum MVar Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
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<td>-40.0</td>
<td>50.0</td>
</tr>
<tr>
<td>3</td>
<td>1.010</td>
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<td>50.0</td>
</tr>
<tr>
<td>6</td>
<td>1.070</td>
<td>-6.0</td>
<td>24.0</td>
</tr>
<tr>
<td>8</td>
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<td>-6.0</td>
<td>24.0</td>
</tr>
</tbody>
</table>

### Table 3.4 Static Capacitor Data

<table>
<thead>
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<th>Bus Number</th>
<th>Susceptance (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.19</td>
</tr>
</tbody>
</table>
3.4 GIC CALCULATION

Since geographic location plays a key factor in a geomagnetic disturbance, all the buses are assigned arbitrary geographic coordinates and sorted into substations.

*Table 3.5 Substation Records*

<table>
<thead>
<tr>
<th>Substation</th>
<th>Buses</th>
<th>Geographical Co-ordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude</td>
</tr>
<tr>
<td>Substation A</td>
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</tr>
<tr>
<td>Substation B</td>
<td>2</td>
<td>34.31</td>
</tr>
<tr>
<td>Substation C</td>
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</tr>
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<td>Substation D</td>
<td>8</td>
<td>34.25</td>
</tr>
<tr>
<td>Substation E</td>
<td>5 &amp; 6</td>
<td>33.55</td>
</tr>
<tr>
<td>Substation F</td>
<td>4,7 &amp; 9</td>
<td>32.97</td>
</tr>
<tr>
<td>Substation G</td>
<td>10 &amp; 11</td>
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</tr>
<tr>
<td>Substation H</td>
<td>12,13 &amp; 14</td>
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</table>

The relations used to calculate distance from one degree of latitude and longitude is as follows:

\[
1^\circ \text{ latitude} = 111.133 - 0.560 \times \cos(2\varphi) \text{ km} \tag{3.2}
\]

\[
1^\circ \text{ longitude} = \frac{111.32}{\sqrt{1 - 0.669 \times \sin(\varphi)^2}} \text{ km} \tag{3.3}
\]
From Equation 3.1, the voltage generated in a transmission line from Bus 1 to Bus 2 is calculated to illustrate the use of this tool. In case of a uniform electric field, the co-ordinates used in equations 3.2 and 3.3 is the average of the co-ordinates at either points of the transmission line. In this thesis, a uniform electric field is simulated for computational convenience and illustrative ease.

Considering the transmission line from Bus 1 to Bus 2, the potential developed during a geomagnetic storm of intensity 3.4 V/km uniform electric field aligned at a direction 90°.

\[ E_x = 3.4 \times \cos(90°) = 0; \quad E_y = 3.4 \times \sin(90°) = 3.4 \text{ V/km}. \]

\[ L_x = (34.3100-33.6130) \times 110.922; \quad L_y = (87.3740-86.3660) \times 92.950 \]

According to equation 3.1,

\[ V_{\text{ind}} = E \cdot L = E_x \cdot L_x + E_y \cdot L_y \]

\[ = 0 \times 110.922 + 3.4 \times 92.950 \]

\[ = 316.03 \text{ V}. \]

Likewise, the induced voltage in all the transmission lines are calculated and tabulated. This obtained voltage is then used to calculate the GIC current circulating in the grid between different buses.
CHAPTER 4: INVESTIGATION OF GIC EFFECTS ON TRANSFORMERS

The most serious hazard that has been observed during previous instances of a Geomagnetic storm is the damage to HV transformers. Grounded neutrals of High Voltage Power Transformers have been identified as the entry points of GIC into the power system. Due to the penetration of these stray currents into the system, there is a pronounced deviation in the operating point of the transformer leading to several undesirable effects propagated through the transmission lines into the entire grid. This chapter attempts to dissect and observe the impacts of GIC on a HV Transformer using simulations in the SimPower Systems Toolbox in MATLAB. Section 4.1 gives a brief overview of the toll of GIC on the operation of the transformer whilst the following sections elaborate and illustrate the issue in further detail.

4.1 INTRODUCTION

GIC currents entering and exiting along several grounded points, flow through the windings of HV transformers driving the core into magnetic saturation. Normally, transformers are designed to operate at the knee point of the saturation curve to extract maximum efficiency. Owing to superimposition of GIC currents, the transformer operating point shifts into the saturation region from the linear region. A small magnitude of DC current is enough to disrupt the operation of the transformer. This susceptibility of transformers to GIC currents makes researchers attribute them to be the weakest links in the entire power grid. Owing to the large scale geographical impact of a Geomagnetic storm, a multitude of transformers are severely affected simultaneously.
Such cumulative and concurrent damage of transformers over a small zone can be overwhelming for the operator at the control station to handle because of the impulsive nature of the phenomenon. It also becomes particularly difficult if there is no prior analysis or specific guidelines to deal with such an event. The present industry strategy is to deal with a disruption using the ‘N-1’ operation criterion giving it the ability to withstand the next disruption and prevent a collapse. The simultaneous failure of several power system assets is one scenario that is held unlikely disregarding the possibility of a Geomagnetic storm in the ‘N-1’ NERC operation criteria.

Ideally, in the AC power system, transformers are designed to operate on sinusoidal waves, but in practice DC currents are superimposed causing a combination of AC and DC excitation in the transformer core. Due to this combined excitation of the core, several issues arise, much to the detriment of the functioning of the transformer.

As discussed earlier, GICs arise because of the sudden, drastic variation of the normally dormant geomagnetic field. The slow varying GIC currents which appear as DC to the predominantly AC power system causes severe bias to the transformer core. This phenomenon is termed as Half Wave or Half Cycle Saturation.

Half Cycle Saturation causes several undesired effects like harmonics in secondary and excitation currents, distortion of core hysteresis curve, increased reactive power consumption and power losses, heating and charring of windings and other tank parts leading to decrement of normal life expectancy, failure and break down of the transformer.
4.2 HALF CYCLE SATURATION IN TRANSFORMERS

Previous research on transformer biasing suggests that the core undergoes a phenomenon called Half Cycle Saturation on injection of GIC. The entire phenomenon is as illustrated below.

Transformers are designed to operate in the linear region as shown in the figure where the excitation current \( I \) has a linear relation with the flux \( \Phi \) produced in the windings. In steady-state operation, almost all the flux is confined to the core of the transformer. The operation of a transformer is constrained by their magnetic constraints of the steel core. Excessive flux causes the core to operate beyond its saturation limits in the saturation region. This excessive flux pulls even more exciting current into the core affecting its linearity resulting in increased losses in the core and harmonics in the current \( I \).

\[ \text{Figure 4.1 Flux-Magnetization Current curve for a transformer [2].} \]
As GIC enters the windings of the transformer through the grounded neutral, the quasi DC currents cause additional flux due to the high number of windings. This excessive flux biases the operating point of the Flux-Magnetization characteristics into the saturation region from the linear region. Now, the core is not only excited by the sinusoidal excitation current but also the quasi dc GIC current. Thus, in one cycle, the ac flux and dc bias are in the same direction causing an excursion in the flux-current operating point.

The Flux-Magnetization characteristics of a transformer with GIC is biased in one half cycle as the MMF due to GIC and normal MMF used to magnetize the core are in the same direction indicating non-linear operation in one cycle of operation and hence the name Half Cycle saturation. The Flux-Magnetization current characteristics of the transformer with GIC operating in the saturation region and under normal conditions in the linear region are juxtaposed in Fig for illustrative purposes.

The continuous operation of the transformer in the saturation region causes the core to saturate with flux. After a few cycles of operation, magnetic reluctance increases owing to core saturation and the excess flux induced due to the DC bias tends to escape and stray out of the core and penetrates into the other internal components of the transformer tank as indicated by magnetic simulations.
Thus, a higher excitation current is required to maintain the same flux in the core so as to maintain sinusoidal output voltage. In addition, the non-linearity of the core incites harmonics in the excitation current. Since the core is now a high reluctance path, a lot of stray flux is generated which causes heating in the windings, loss of insulation, formation of hot spots leading to structural damage and subsequently equipment failure.
4.3 SIMULINK MODEL OF INDUCTANCE MATRIX TRANSFORMER

To illustrate all the above discussed phenomena on transformers, a simulation model was developed in Simulink using the SimPower systems toolbox. The default transformer model does not allow current in the grounded neutral of the transformer to be directly coupled with the inductance of the winding. Hence, the Inductance Matrix type transformer model is used for simulation in this thesis.

The transformer model can be expressed as

$$
\begin{bmatrix}
V_1 \\
\vdots \\
V_6 \\
\end{bmatrix} =
\begin{bmatrix}
R_1 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & R_6 \\
\end{bmatrix}
\begin{bmatrix}
I_1 \\
\vdots \\
I_6 \\
\end{bmatrix}
+ \begin{bmatrix}
L_{11} & \cdots & L_{16} \\
\vdots & \ddots & \vdots \\
L_{61} & \cdots & L_{66} \\
\end{bmatrix}
\begin{bmatrix}
I_1 \\
\vdots \\
I_6 \\
\end{bmatrix}
+ \frac{d}{dt} \begin{bmatrix}
I_1 \\
\vdots \\
I_6 \\
\end{bmatrix}
$$

\hspace{2cm} \text{-----------------------------------} (4.1)

R1……R6 represent Winding Resistances.

L11……L66 represent Self Inductances.

L12……L65 represent Mutual Inductances.
The Inductance matrix model type has a limitation of no provision for Core Saturation. Hence, to implement saturation, an external saturation block is set up in parallel with the primary winding of the saturable transformer while using the same specifications such as winding configuration (Yg, D1 or D11), same winding resistance for the two windings connected in parallel and desired saturation characteristics.

Figure 4.4 Configuration & Parameters Tab of the Transformer Model

Core Type: The Core Type selected for the simulation is a three limb core which implies that both positive and zero sequence parameters are used to calculate the Inductance Matrix in equation (1).
**Winding connections**: The primary winding is of Y-grounded configuration with accessible neutral while the secondary winding is Y-grounded.

Since the Inductance Matrix model of the transformer involves coupling of the phases in the core type of construction to minimize the quantity of iron in the core, the model has different reactance and excitation currents in the positive and zero sequences.

Due to imbalances in the voltage source or load, there is a zero sequence component of voltage in addition to the positive and negative sequences which leads to higher excitation currents. These can be measured by using Positive and Zero sequence measurement blocks as shown in fig

![Diagram of transformer connections](image)

*Figure 4.5 Calculation of Positive and Zero-Sequence parameters*
The externally setup saturation block consists of the three phases of the windings with a common grounded neutral. All the phases are saturable as depicted in the fig but owing to computational difficulties, hysteresis is implemented only in phase A of the primary winding. The Saturation characteristics defined are default specifications for the 500kV/230kV transformer.

![Diagram of the saturation block](image)

**Figure 4.6  External Saturation block for the transformer**
4.4 CIRCUIT DESCRIPTION

The entire circuit is laid out for simulation purposes in the Simulink window as shown in Fig 5.7. It is used to demonstrate the operation of a 3 Ø, two winding, 500kV / 230kV step down transformer along with saturation modeling. The details of the circuit are as follows:

- The source is a 3000 MVA, 500 kV phase-phase equivalent block which excites the primary winding of the transformer.
- GIC is introduced as a slow varying ac current source in the grounded neutral of the primary winding.
- The Saturation block is setup in parallel to the primary winding.
- Three phase V-I measurement blocks B1 & B2 are used in the primary and secondary windings respectively.
- Transmission line to a 3 Ø Load is simulated using a Distributed Parameters Line block.
- The load which is assumed to be 20% of the Nominal Power of the transformer is simulated using a 3 Ø RLC parallel load.

The remaining blocks in the circuit which are used to illustrate GIC effects will be discussed in detail in the following section.
Modeling GIC effects in a 450 MVA, 500e3V/230e3V Three-Phase Core-Type Inductance Matrix Transformer

Figure 4.7 Simulink Model illustrating GIC effects on Transformer
4.5 ILLUSTRATION OF GIC EFFECTS IN SIMULINK

To demonstrate the effects of GIC on a transformer, several other blocks in the SimPower systems toolbox are added to the Simulink model as shown in the above figure. The following sections describe in detail the effects of GIC on the transformer unit and half cycle saturation of the core.

4.5.1 DISTORTION OF SATURATION CHARACTERISTICS

The excess flux that saturates the core, biases the operating point of the transformer into saturation region in the ‘$\Phi$- $I$’ curve thereby disturbing the equilibrium and causing non-linear operation of the core in one half cycle. As additional flux is thrust upon the core, it gets saturated to greater flux linkages than it was intended to be. Thus, the current produced in the primary winding is not proportional to that in the secondary winding and hence the efficiency is severely reduced.

Saturation limit is a measure of how much magnetic flux linkage is achievable between the primary and the secondary windings of the core thus influencing the core size. Saturation characteristics represent the piece-wise linear relationship between Flux and the Magnetizing Current of the transformer. The default characteristics specified as ($\Phi$, $I$) pairs also represent the hysteresis modeling using a static model in the Power System Block set (PSB)[27]. Under normal operation, the flux produced in the primary winding core $\Phi_{ac}$ is 1 p.u which is near the knee point of the operation curve.
When the quasi-dc GIC current $I_{dc}$ enters the windings through the neutral, it creates additional flux $\Phi_{dc}$. Even for a small magnitude of dc current entering the transformer, a large amount of dc flux is generated due to the high number of turns.

$$\Phi_{dc} = N_1 \cdot I_{dc}$$  \hspace{1cm} (4.2)

Hence, the total flux produced in the core $\Phi_t = \Phi_{ac} + \Phi_{dc} = F (I_{ac} + I_{dc})$

Where $\Phi_{ac}$, $\Phi_{dc}$ are fluxes produced by ac and dc currents respectively.

$I_{ac}$ is the ac current flowing through the windings, $I_{dc}$ is the GIC current entering the winding and $F$ being the $\Phi$- $I$ curve of the transformer.

![Flux - Current characteristic](image)

*Figure 4.8 Saturation characteristics for transformer core for rated conditions*
Figure 4.9 Saturation characteristics of a 10A GIC saturated transformer core

As this flux saturates the core, excitation currents of higher magnitude and different harmonics are required to maintain the flux linkage between the primary and secondary windings leading to distorted saturation characteristics.

In the simulation, the flux-current characteristics are plotted using an XY signal scope after converting both the quantities into per unit system. Using the transformer model and different blocks in the SimPower Systems library, this is illustrated for different GIC levels entering the transformer through the grounded neutral and the results are tabulated in Chapter 6.
4.5.2 HARMONICS IN CURRENT WAVEFORMS

The power system in the US runs at 60 Hz but disturbances such as GIC create currents which run at a frequency which are integer multiples of 60 Hz. These are called harmonic disturbances and this phenomenon is a perennial problem in the operation of the power system. A Harmonic disturbance can be described as a steady state periodic phenomenon which causes continuous distortion in the normally sinusoidal voltage and current waveforms. These disturbances can be characterized by their magnitudes and phase angles which can be computed using the Fourier analysis technique [28].

Using Fourier analysis, a periodic waveform can be decomposed into a continuous series of terms each representing a component of the integer multiple of the fundamental frequency (60Hz).

Harmonic analysis is an important step in order to analyze the response of the power system to GIC so that necessary mitigation steps can be formulated. Hence, it is necessary to measure the harmonics that are generated in the currents due to the entry of GIC into the power grid via the transformer. Thus, Fourier analysis has been carried on several currents waveforms to measure their respective harmonic contribution.

As the transformer displays non-linear behavior due to saturation, it generates harmonics in the Excitation current $I_{exc}$ and the primary and secondary currents $I_p$ and $I_s$ leading to increased harmonic distortion in current waveforms associated with the transformer.
The normal excitation current of the transformer is found to be 5.625 A for phase A.

With gradual increase in GIC, there is a corresponding increase in the magnitude of the excitation current $I_{\text{exc}}$ illustrated in the following graph Fig 5.8.

![Variation of Excitation Current $I_{\text{exc}}$ with GIC](image)

*Figure 4.10 Variation of Excitation Current $I_{\text{exc}}$ with GIC Injection*

As GIC increases beyond a certain threshold (in this case 20A), $I_{\text{exc}}$ shoots up drastically owing to the saturation of the core and its non-linear behavior.
Apart from increased magnitude, there is also a pronounced increase in the harmonic content of the current waveforms. To analyze this, FFT computation is performed on the waveforms.

The Fourier series of any waveform in time domain can be written as:

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L} \right)$$

Where $a_0$ is the dc component of the signal while each term represents the harmonics of the signal.

Thus, for the current waveform

$$I(t) = I_0 + \sum_{n=1}^{\infty} (a_n \cos(n\omega t) + b_n \sin(n\omega t))$$

$$= I_0 + \sum_{n=1}^{\infty} (I_n \sin(n\omega t + \Theta_n))$$

Where $I_0$ represents the DC current component, $I_n$ is the peak magnitude of the $n^{th}$ harmonic with $'\omega'$ being the fundamental frequency and $\Theta_n$ being the respective phase angle of individual harmonic components.

To perform this computation, the FFT (Fast Fourier Transform) Analysis Tool in the PowerGUI block is used, shown in the Fig 4.11.
Using this tool, the contribution of each harmonic in the waveform can be computed. Ideally, the fundamental frequency (60 Hz) should be the harmonic present in the signal but in practice, we see the presence of various other harmonics.
4.5.2.1 TOTAL HARMONIC DISTORTION

Total Harmonic Distortion (THD) is a measure of the harmonic disturbance present in the current waveforms. It can be defined as the value of the RMS value of all the harmonics except the fundamental with respect to that of the RMS value of the fundamental.

\[
\text{THD} = \left( \frac{RMS \text{ value of the harmonic content except the fundamental frequency}}{RMS \text{ value of the fundamental frequency}} \right)
\]

\[
= \left( \frac{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots + I_n^2}{I_1^2} \right)^{0.5} / I_1
\]

Where \( I_1, I_2, I_3, I_4, \ldots, I_n \) are RMS values of respective harmonic currents.

Every utility sets its own limits of acceptable THD in the current and voltage waveforms. Usually, the amount of acceptable THD in voltage waveforms is below 10%. Any increase in THD beyond the limits set causes problems like Voltage drops, Capacitor tripping, increased power losses and voltage stresses on sensitive loads.

Maintaining THD within tolerable limits is an important part of keeping power quality. Much research has been done on this subject and its discussion is beyond the scope of this thesis. IEEE 519 standard is useful in formulating harmonic standards for electrical systems.
Figure 4.12 FFT Analysis of Primary winding current $I_{abc\_B1}$ for rated conditions.
From the Fourier analysis of the primary winding current $I_{abc-B1}$, we observe that during normal operation, the fundamental frequency (60 Hz) has the major contribution to the signal while the other harmonic contributions ($h_2, h_3, h_4...$) and the dc component are negligible compared to the $h_1$.

The THD is computed from the equation shows that the current & voltage distortions are 1.03% and 0.12% respectively which are within acceptable limits.

But, in the presence of GIC, the saturated core operating in the non-linear region of the $\phi-I$ curve derives harmonics of excitation current $I_{exc}$ and these harmonics are further propagated into the system through the primary winding towards the voltage source and through the secondary winding into the load and other power system equipment like capacitor banks susceptible to harmonic currents with high levels of harmonic distortion.
Figure 4.13 FFT Analysis of Primary winding current $I_{abc\_B1}$ for GIC=25 A

Sampling time = 5.0050e-005 s
Samples per cycle = 333
DC component = 23.41
Fundamental = 167.4 peak (118.3 rms)

Total Harmonic Distortion (THD) = 28.29%

Maximum harmonic frequency
used for THD calculation = 9900.00 Hz (165th harmonic)

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>THD (%)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Hz (DC)</td>
<td>13.99%</td>
<td>270.0°</td>
</tr>
<tr>
<td>60 Hz (Fnd)</td>
<td>100.00%</td>
<td>-13.5°</td>
</tr>
<tr>
<td>120 Hz (h2)</td>
<td>20.03%</td>
<td>260.2°</td>
</tr>
<tr>
<td>180 Hz (h3)</td>
<td>14.41%</td>
<td>264.0°</td>
</tr>
<tr>
<td>240 Hz (h4)</td>
<td>9.74%</td>
<td>254.9°</td>
</tr>
<tr>
<td>300 Hz (h5)</td>
<td>7.16%</td>
<td>249.5°</td>
</tr>
<tr>
<td>360 Hz (h6)</td>
<td>4.68%</td>
<td>251.3°</td>
</tr>
<tr>
<td>420 Hz (h7)</td>
<td>3.00%</td>
<td>231.9°</td>
</tr>
<tr>
<td>480 Hz (h8)</td>
<td>2.42%</td>
<td>225.5°</td>
</tr>
<tr>
<td>540 Hz (h9)</td>
<td>1.29%</td>
<td>254.7°</td>
</tr>
<tr>
<td>600 Hz (h10)</td>
<td>0.55%</td>
<td>216.3°</td>
</tr>
<tr>
<td>660 Hz (h11)</td>
<td>0.09%</td>
<td>187.5°</td>
</tr>
<tr>
<td>720 Hz (h12)</td>
<td>0.35%</td>
<td>78.5°</td>
</tr>
<tr>
<td>780 Hz (h13)</td>
<td>0.26%</td>
<td>30.3°</td>
</tr>
</tbody>
</table>
After FFT Analysis of the Primary winding current $I_{abc\text{-}B1}$ in the presence of a GIC of 25 A, we see that there is an increase in the contribution of higher harmonics ($h_2, h_3, h_4, \ldots$) and the dc component increases to a large extent and these are not negligible to that of the fundamental frequency $h_1$.

In addition to harmonics in winding currents, extremely large harmonics are witnessed in the excitation current of the transformer. With the on-set of GIC, the spectrum of $I_{exc}$ contain more harmonic components which excite the core improperly leading to excessive flux and non-linear relation between the flux $\phi$ and $I_{exc}$.

![Figure 4.14 Waveform and Spectrum of RMS Excitation current $I_{exc}$ with GIC =25 A](image_url)
4.5.3 INCREMENT IN REACTIVE POWER CONSUMPTION

GIC saturation makes transformer behave as a source of harmonics causing a drastic increase in Reactive power consumption which has profound effect over the system stability. The reactive power consumption of the transformer block in phase A is observed using the Active & Reactive power block in SimPower Systems Library. This sudden fluctuation in VAR consumption is attributed to be the main reason for several other problems like Voltage Stability and decrease in power quality.

As excess flux starts building up in the core, it is driven into saturation and causes harmonics in the exciting current $I_{exc}$. These harmonics result in an increase in the VAR Consumption for the obvious reason that they excite the core without being in phase with the fundamental frequency $h_1$.

Half cycle saturation reduces the magnetizing reactance of the transformer causing a surge in the magnitude of the excitation current causing the transformer to behave as an inductive load ultimately resulting in an increase in VAR demand [29].

In the presence of GIC, non-sinusoidal excitation is present in the transformer which leads to improper excitation of the core and harmonics in $I_{exc}$. These harmonics cause higher VAR consumption than normal.
The VAR consumption in presence of non-sinusoidal currents can be defined as the product of the AC voltage and the harmonic components of the currents [30]:

\[ Q = V \sqrt{\sum_{i=1}^{N} I_i^2} \]  \hspace{1cm} (4.6)

Where \( Q \) is the Reactive power consumption in VARS

\( V \) is the RMS AC voltage in Volts

\( I_i \) is the respective harmonic current magnitude in Amperes.

As GIC injection into the transformer increases, we see the appearance higher degree harmonics in the currents leading to increased reactive power consumption. As a secondary effect, the Active power (P) also decreases due to losses caused by the deformation of transformer windings as a result of repeated excitation by current harmonics.

For this task, the Active and Reactive Power block from the SimPower systems library is used. The block measures the active power \( P \) and reactive power \( Q \) of a voltage-current pair that contains harmonics with the output being the vector \([P \ Q]\) based on the following integral equations:

\[ P = \frac{1}{T} \int_{t-T}^{t} V(\omega t) \cdot I(\omega t) \, dt \]  \hspace{1cm} (4.7)

\[ Q = \frac{1}{T} \int_{t-T}^{t} V(\omega t) \cdot I(\omega t - \pi/2) \, dt \]  \hspace{1cm} (4.8)
In the simulation, using the voltage and current measured on phase A, the Active power ‘P’ and Reactive power ‘Q’ of the transformer are calculated for different levels of GIC injected through the grounded neutral of the transformers. Figs 5.13 & 5.14 elaborate the sharp increase in VAR consumption along with a drop in Active power P signifying increased losses.

![Figure 4.15 Active Power profile with increase in GIC](image1)

*Figure 4.15 Active Power profile with increase in GIC*

![Figure 4.16 Reactive Power profile with increase in GIC](image2)

*Figure 4.16 Reactive Power profile with increase in GIC*
In the IEEE 14 Bus simulation in PowerWorld simulator, the reactive power loss in a transformer due to GIC is calculated by solving a simple DC circuit at its respective bus. As explained in Section 3.4, voltage induced due to a geomagnetic storm is calculated at every bus taking into account the geographic location of the substation it is present at.

Then, using Ohm’s law, the current developed in the neutral of the transformer due to this induced voltage \( V_{\text{ind}} \) is calculated by dividing it with the sum of the corresponding substation resistances, per phase transmission line and coil resistances of the transformer.

*Table 4.1 Transformer VAR loss tabulation.*

<table>
<thead>
<tr>
<th>From Number</th>
<th>From Name</th>
<th>To Number</th>
<th>To Name</th>
<th>Circuit</th>
<th>Manually Enter Coi Resistance</th>
<th>Transformers Phase 1 Ohms Per Phase</th>
<th>Transformers Phase 2 Ohms Per Phase</th>
<th>Is Auto-transformer</th>
<th>Transformer GIC Neutral Amps</th>
<th>Transformer GIC Var Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 Bus 4</td>
<td>7 Bus 7</td>
<td>1</td>
<td>No, Auto De</td>
<td>0.0010000</td>
<td>Unknown</td>
<td>NO</td>
<td>0.0000</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>4 Bus 4</td>
<td>9 Bus 9</td>
<td>1</td>
<td>No, Auto De</td>
<td>10.00000</td>
<td>10.00000</td>
<td>NO</td>
<td>98.025</td>
<td>79.77</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5 Bus 5</td>
<td>6 Bus 6</td>
<td>1</td>
<td>No, Auto De</td>
<td>10.00000</td>
<td>10.00000</td>
<td>Unknown</td>
<td>NO</td>
<td>-42.783</td>
<td>44.73</td>
</tr>
<tr>
<td>4</td>
<td>8 Bus 8</td>
<td>7 Bus 7</td>
<td>1</td>
<td>No, Auto De</td>
<td>10.00000</td>
<td>Unknown</td>
<td>NO</td>
<td>0.0000</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7 Bus 7</td>
<td>9 Bus 9</td>
<td>1</td>
<td>No, Auto De</td>
<td>0.000000</td>
<td>10.00000</td>
<td>Unknown</td>
<td>NO</td>
<td>23.996</td>
<td>21.02</td>
</tr>
</tbody>
</table>

With the obtained neutral current and the voltage induced, the excess reactive power consumed by the transformer is calculated. By carrying out these calculations for every transformer present in the system, the total VAR loss in the system is estimated for a particular magnitude of a geomagnetic storm.
4.5.4 THERMAL DEGRADATION & STRUCTURAL DEFORMATION

As discussed earlier, when the core gets saturated with flux, there is a sharp increase in its reluctance as compared to the surrounding. Thus, the leakage flux exits through plausible locations of the core into the transformer tank. This additional flux leads to eddy current activity which causes intense heating in the tank wall, shunts, clamps and other structural parts of the transformer [31].

The core saturation results in internalized local heating and charring of the windings and damage to the insulation. Structural deformation follows as the leakage flux escapes out of the core into the transformer tank and formation of high temperature zones called ‘hotspots’ in the transformer unit reducing the life of the transformer and its efficiency.

A brief account of previous encounters of Transformers with GIC is as follows:

a. The March 1989 Geomagnetic storm resulted in a Generator Step-Up Unit at Salem Nuclear Power Plant operated by PSE&G was damaged and had to be taken off-service due to excessive GIC heating. The GSU was a bank of three single phase transformers rated at 500 kV Y-24kV Δ recorded a sudden increase in Reactive power consumption by 50 MVar along with high content of dissolved gases combustible gases in cooling oil and noise levels. On inspection after the incident, charring of windings caused by circulating currents and the impingement of flux on structural parts not expected during normal operation, has been observed as shown in Fig 5.15 [2].
b. A 3-Ø shell form 500kV/138kV autotransformer operated by Allegheny Power System at Meadowbrook Substation also saw significant damage during the 1989 Geomagnetic storm. Drastic increase in MVar consumption and high level of THD in the currents were attributed to be the main reason for the breakdown leading to high amount of dissolved combustible gases in insulation oil and intense heating. Analyses post the disruption showed that the temperature measured on the walls of the tank ran up to 173°C [2].

c. During the 2003 Halloween Storm, several transformers operated by Eskom Power Corp., in South Africa were reported to have contained high content of dissolved gases due to excessive saturation of the core. A comparison of Dissolved Gas Analysis (DGA) records prior to and after the storm has shown that after the onset of GIC, there was a marked increase in the reactive loading.
Unintended tripping of transformer protection and partial breakdown of winding insulation has been attributed to the high amount of harmonic content in the currents and intense localized heating. Subsequently, the units had to be promptly removed out of service [32].

Apart from these, there have been several other reported incidents of transformer disruption, failure and breakdown due to GIC activity in them located in countries like the UK, New Zealand and Japan etc [2].

Failure of transformer units of such high voltage levels is a huge setback to the operation of the transformer, as they are huge and expensive to construct and assemble along with the long lead-time associated with their replacement. A GSU Transformer is even more difficult to supplicate with absence of redundancy unlike a transmission network transformer. Owing to the wide area scope of a geomagnetic storm, multiple simultaneous failures can seriously hamper restoration efforts.
CHAPTER 5: VOLTAGE STABILITY AND GRID RESPONSE

In addition to damage to HV Power Transformers, a geomagnetic event has the adverse effect of VAR loss in a power grid thereby causing widespread voltage instability ultimately leading to the collapse of the entire grid. The logical approach in dealing with this problem is to assess the vulnerabilities of the grid to voltage instability using an analytical method so that necessary mitigation measures and methods can be devised and put in place to combat GIC effects. This chapter is based on the paper [34] which predicts voltage stability of a bus system systematically. Section 5.1 introduces the concept of Voltage Stability and the following sections describe a method to assess it.

5.1 INTRODUCTION

Voltage stability refers to the capacity of a power network to maintain steady, permissible voltage levels at all the buses perpetually even after experiencing a disturbance or a contingent event. Voltage stability analysis warrants observation of voltage profiles when a contingency occurs. During voltage stability, there is a loss in the stable operating point of the grid due to the diminution of voltage levels around the point of voltage collapse. Disproportion between ‘P’ and ‘Q’ leads to bus voltage fluctuation and these values at each bus indicate the degree of this discrepancy. In this case, since voltage instability is an issue that is expected to arise due to fluctuation or loss of reactive power support in the grid, a method that relates the voltage at each bus and the reactive power support is required. In practice, not every bus is the grid can be assessed for stability.
Thence, it is a crucial step in locating the critical bus or the group of buses which are likely to experience voltage instability during a contingency. According to [37], a critical bus can be characterized as having the following qualities during a contingency:

- Highest voltage collapse point on the V-Q curve
- Smallest reactive power margin
- Greatest reactive power deficiency
- Greatest excursion in voltage levels.

PV & QV curves are generally used to assess the voltage stability at a particular bus. They represent the variation of bus voltages with Power Injection. By using the QV curve, it is possible to estimate the amount of VAR support that can be attained or lent to achieve voltage stability at the bus most vulnerable to voltage collapse.

Based on the stability margin obtained from the curve, reactive power producing systems such as SVC (Static VAR Compensators) & STATCOM (Static synchronous compensator) can be installed to maintain required voltage levels. But, for large systems which contain numerous buses, generating QV curves for each bus is tedious. Hence, a fast computational method is to be adopted in this case. Due to the extensive study of voltage stability analysis, various methods have evolved over the years which can be broadly divided as Static and Analytic methods [35]. Several other methods have been discussed in [36] outlining various approaches in identifying areas and components susceptible to voltage instability.
An expected approach in dealing with Voltage instability due to GIC is that the transient stability of the grid will be assessed, but there arise certain issues. Although Voltage Instability is perceived as a transient phenomenon, problems with using dynamic analysis are computational difficulties owing to the vastness of the grid, the number of constraints that have to be considered and contingencies that arise during analysis. Therefore, in this thesis, a static steady state approach called Modal Analysis technique is used which was put forward by Morison, Gao & Kundur [36].

5.2 SIGNIFICANCE OF REACTIVE POWER

Reactive Power is an important factor in maintaining voltage stability of the grid. It refers to the circulating power in the grid. Due to the inherent nature of loads like motors, there is a shift in the phase between the voltage and current which leads to the formation of this quantity measured in Vars. Insufficient levels of reactive power leads to voltage sags and reduced transmission line limits pushing the grid to the verge of total collapse. The flow of reactive power is important to maintain voltage levels within acceptable limits (±5%) of the nominal voltage. In the absence of adequate flow of ‘Q’, low voltages lead to decreased efficiency in operation of equipment whereas high voltages lead to damage.

System requirements and loading levels govern the requirement of reactive power in the grid. Hence, keeping a reserve of reactive power is increasingly becoming a norm with power system operation. The disadvantage with Reactive power is that cannot be transported very far and thus usually has to be produced at the desired location.
5.3 MODAL ANALYSIS FOR VOLTAGE STABILITY ASSESSMENT

The Modal analysis technique utilizes the Power Flow Jacobian to evaluate the relation between Reactive power injection and Bus voltages by keeping the remaining constraints in the Linearized power flow state equations such as Active Power and Bus Voltage angle constant. The Power flow Jacobian matrix is reduced in order to depict the incremental variation in Voltage with respect to Reactive Power injection at each bus [36].

The Steady state system Power flow equations are given by:

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
= \begin{bmatrix}
J_{p\theta} & J_{pV} \\
J_{q\theta} & J_{qV}
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta V
\end{bmatrix}
\]  

(5.1)

With \( J_{ac} = \begin{bmatrix}
J_{p\theta} & J_{pV} \\
J_{q\theta} & J_{qV}
\end{bmatrix} \) being the Power flow Jacobian matrix of the system.

Where

\( \Delta P = \text{Incremental change in Bus Real power.} \)

\( \Delta Q = \text{Incremental change in Bus Reactive power.} \)

\( \Delta \theta = \text{Incremental change in Bus Voltage Angle.} \)

\( \Delta V = \text{Incremental change in Bus Voltage Magnitude.} \)

In order to study the relation between reactive power and Bus voltage variation, the remaining two quantities in the equation i.e. Real Power and Bus Voltage angle are to be eliminated. This is accomplished by reducing the Jacobian matrix by keeping \( \Delta P = 0 \).
Thus,

\[ \Delta P = 0 = J_{P\theta} \Delta \theta + J_{PV} \Delta V \quad (5.2) \]

Which implies

\[ \Delta \theta = -J_{P\theta}^{-1} J_{PV} \Delta V \quad (5.3) \]

\[ \& \]

\[ \Delta Q = J_{Q\theta} \Delta \theta + J_{QV} \Delta V. \quad (5.4) \]

Substituting the value for \( \Delta \theta \), we deduce a relation between \( \Delta Q \) and \( \Delta V \)

\[ \Delta Q = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}] \Delta V \quad (5.5) \]

\[ \Delta Q = J \Delta V \text{ or } \Delta V = J^{-1} \Delta Q \quad (5.6) \]

\( J \) being the reduced form of the Power flow Jacobian.

Thus,

\[ J = J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV}. \quad (5.7) \]

The matrix \( J \) represents the linearized power flow relation between the Reactive Power Injection and Bus Voltage which is achieved by omitting the Real power and Bus Voltage Angle from the Steady State power flow Equation [38].

The advantage in doing this operation on the Power flow Jacobian is to exclusively focus on the variation of voltage stability due to change in Reactive Power injections at different buses which address the voltage instability issue in the grid.
The obtained reduced Jacobian matrix contains the reactive power and voltage characteristics of the buses. The Eigen values of the matrix signify the different modes of Reactive power and voltage characteristics thereby giving information about the voltage stability of the grid. The magnitudes of the Eigen values give information about the propinquity of the entire grid to voltage instability and the magnitudes of its associated Eigen vectors of each mode give information about the proximity of each bus to voltage instability [36].

The reduced Jacobian matrix ‘J’ can be written as a product of three different matrices:

\[
J = \xi \wedge \eta
\]  

(5.8)

Where \( \xi \) is the right eigen vector of matrix J.

\( \wedge \) is the diagonal eigen vector of matrix J.

\( \eta \) is the left eigen vector of matrix J.

Conversely,

\[
J^{-1} = \xi^{-1} \wedge \eta
\]  

(5.9)

Substituting the value of \( J^{-1} \) in equation 5.6,

\[
\Delta V = \xi^{-1} \wedge \eta \Delta Q
\]  

(5.10)
Or \[ \Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \quad (5.11) \]

where \( \lambda_i \) is the \( i^{th} \) eigenvalue, \( \xi_i \) is the \( i^{th} \) column right eigenvector and \( \eta_i \) is the \( i^{th} \) row left eigenvector of matrix \( J \). The product of the left and right eigen vectors is identity matrix \( I \).

Hence, \[ \Delta V_i = \frac{1}{\lambda_i} \Delta Q_i \] is the \( i^{th} \) modal voltage variation. \( (5.12) \)

Now, the value of the Eigen vector determines the relationship between the voltage and the reactive power value at a particular mode. A positive value of \( \lambda_i \) signifies its stability whereas a negative value signifies instability and a value of ‘ ‘ represents voltage collapse.

Using this method, the tendency of an area to collapse during a contingency can be assessed. This is deemed to be an important step in assessing the vulnerability of the grid as it gives system operators to identify areas exposed to voltage instability due to reactive power loss. The Eigen values represent the V-Q sensitivities at each bus and their magnitude is a measure of voltage instability for that particular bus in the least stable modes in the grid.

The Modal Analysis technique then developed an index called Participation factor. Participation factor indicates the contribution of a specific Eigen value to the voltage sensitivity at a particular bus to identify its vicinity to voltage collapse[36]. Participation factor is calculated from the Eigen vectors of the reduced Jacobian matrix ‘\( \tilde{J} \)’ from equation 5.7.
The participation factor of bus \( k \) during \( i^{\text{th}} \) mode is:

\[
P_{ki} = \xi_{ki} \eta_{ik}
\]  

(5.13)

The value indicates the contribution of the \( i^{\text{th}} \) Eigen value to the Q-V sensitivity at bus \( k \). The magnitude of this value represents the tendency of its corresponding eigen value \( \lambda_i \) to cause voltage instability at bus \( k \). Since, the modes with smallest Eigen values are close to voltage instability; their corresponding Bus Participation factors are calculated. The Buses are then ranked in terms of their participation factors which indicate decreasing voltage stability.

To perform all these operations, the Power flow Jacobian in PowerWorld Simulator was saved as a sparse matrix .m file. A function called modal (); was then developed in MATLAB to execute the whole process.

By identifying and ranking the buses in terms of their tendency to voltage collapse, this method eliminates the need to generate Q-V curve for every bus in the system. Utilizing the participation factor in the weakest mode, buses can be ranked in terms of their proximity to voltage collapse at different operating points. The bus with the highest participation in the critical mode is said to be the weakest bus in terms of voltage stability and thus its Q-V curve is generated to calculate its Reactive Power Margin (RPM). For the purpose of this simulation, three different contingencies were chosen corresponding to increasing magnitudes of induced electric field ‘E’. To better observe the dynamic nature of voltage variation with increasing Reactive Power loss, a color contour was used a background in the test system.
5.4 Q-V CURVE GENERATION

The next step in voltage stability assessment is to generate Q-V curves at the critical bus i.e., the bus which is more prone to voltage collapse. Load buses are generally the weakest buses in a power system as they do not have a continuous generation of reactive power. Hence, they are highly sensitive to any kind of voltage disturbance. Q-V curve gives system designers a notion of the reactive power injection required at a particular bus to attain voltage security. A typical Q-V curve is shown in the Figure 5.1.

![Figure 5.1 Standard Q-V curve [38].](image)

The distance from the stable operating point to the point of $Q_{\text{max}}$ is defined as the Reactive Power Margin (RPM) at the bus. Apart from the calculation of RPM, Q-V curves aid in identifying whether a bus has a stable operating point or not.
The slope of the curve represents the V-Q sensitivity \( \frac{\partial V}{\partial Q} \) at a particular operating point.

The upper part of the curve is designated as the stable region as the V-Q sensitivity is positive in that region indicating the fact that as reactive power injection increases, voltage increases. When the reactive power reserve is depleted due to losses at a bus in such a way that it reaches the critical point \( Q_{\text{max}} \), anymore further injection beyond this point causes a voltage drop indicating a negative V-Q sensitivity and voltage instability.

In order to generate this curve, a fictitious generator is placed on a bus whose reactive power output is of interest. By varying the voltage set point in small steps, the VARs required to maintain this voltage is then measures and the co-ordinates are plotted on a curve with Voltage and VAR output being its axes.

At rated conditions, the output of the fictitious generator is ‘0’. As the reactive power losses due to GIC mount, they behave as increasing MVar load on the system depleting the RPM at the weakest bus. When the losses increase to such an extent that it consumes the entire RPM, then voltage collapse ensues.

For the IEEE 14 bus system used in this thesis, after identifying and ranking the critical bus or cluster of buses, their QV curves are observed to see how sensitive they are to a geomagnetic storm and their voltage stability is determined at three different operating points. The results are laid down in Chapter 6 for further illustration.
6.1 RESULTS FROM TRANSFORMER ANALYSIS

Figure 6.1 THD versus GIC injection for phase A

Figure 6.1 represents Total Harmonic Distortion (THD) versus injected GIC current into the transformer. With steady increase in GIC, THD also increases due to increment in harmonic content. After reaching a certain point, any further increase in GIC causes a drop in THD as the dc starts dominating in the current. Table 6.1 contains data about THD of primary and secondary, voltages and currents which indicate escalating harmonics with increasing GIC.
Table 6.1 Transformer Current & Voltage Distortion Results

<table>
<thead>
<tr>
<th>GIC(A)</th>
<th>I_p</th>
<th>V_p</th>
<th>I_s</th>
<th>V_s</th>
<th>I_{exc}(A)</th>
<th>P  (W)</th>
<th>Q  (Var)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.03</td>
<td>0.12</td>
<td>0.09</td>
<td>0.09</td>
<td>-5.626</td>
<td>3.39E+07</td>
<td>-1.27E+06</td>
</tr>
<tr>
<td>5</td>
<td>1.37</td>
<td>0.15</td>
<td>0.11</td>
<td>0.11</td>
<td>-8.704</td>
<td>3.38E+07</td>
<td>-1.15E+06</td>
</tr>
<tr>
<td>10</td>
<td>2.50</td>
<td>0.23</td>
<td>0.18</td>
<td>0.18</td>
<td>-15.67</td>
<td>3.38E+07</td>
<td>-7.15E+05</td>
</tr>
<tr>
<td>15</td>
<td>4.67</td>
<td>0.41</td>
<td>0.33</td>
<td>0.33</td>
<td>-28.09</td>
<td>3.36E+07</td>
<td>1.26E+05</td>
</tr>
<tr>
<td>20</td>
<td>8.53</td>
<td>0.73</td>
<td>0.59</td>
<td>0.59</td>
<td>-49.03</td>
<td>3.35E+07</td>
<td>1.59E+05</td>
</tr>
<tr>
<td>25</td>
<td>28.28</td>
<td>7.34</td>
<td>2.92</td>
<td>2.92</td>
<td>-141.1</td>
<td>3.32E+07</td>
<td>5.68E+06</td>
</tr>
<tr>
<td>30</td>
<td>52.03</td>
<td>5.81</td>
<td>4.95</td>
<td>4.95</td>
<td>-248.3</td>
<td>3.27E+07</td>
<td>1.28E+07</td>
</tr>
<tr>
<td>35</td>
<td>64.73</td>
<td>7.49</td>
<td>6.53</td>
<td>6.53</td>
<td>-342.3</td>
<td>3.22E+07</td>
<td>2.04E+07</td>
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<tr>
<td>40</td>
<td>68.70</td>
<td>9.08</td>
<td>7.71</td>
<td>7.71</td>
<td>-426.3</td>
<td>3.17E+07</td>
<td>2.80E+07</td>
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<td>45</td>
<td>68.07</td>
<td>10.30</td>
<td>8.53</td>
<td>8.53</td>
<td>-502.3</td>
<td>3.11E+07</td>
<td>3.52E+07</td>
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<td>50</td>
<td>65.36</td>
<td>13.46</td>
<td>9.79</td>
<td>9.79</td>
<td>-571.8</td>
<td>3.06E+07</td>
<td>4.20E+07</td>
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<td>55</td>
<td>61.57</td>
<td>25.89</td>
<td>11.56</td>
<td>11.56</td>
<td>-641</td>
<td>3.01E+07</td>
<td>5.01E+07</td>
</tr>
<tr>
<td>60</td>
<td>58.28</td>
<td>13.15</td>
<td>12.72</td>
<td>12.72</td>
<td>-730.3</td>
<td>2.93E+07</td>
<td>5.96E+07</td>
</tr>
<tr>
<td>65</td>
<td>54.67</td>
<td>13.82</td>
<td>13.53</td>
<td>13.53</td>
<td>-750.3</td>
<td>2.91E+07</td>
<td>6.02E+07</td>
</tr>
<tr>
<td>70</td>
<td>51.21</td>
<td>14.22</td>
<td>14.13</td>
<td>14.13</td>
<td>-801.8</td>
<td>2.87E+07</td>
<td>6.74E+07</td>
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<tr>
<td>75</td>
<td>47.95</td>
<td>14.40</td>
<td>14.62</td>
<td>14.62</td>
<td>-850.2</td>
<td>2.83E+07</td>
<td>7.28E+07</td>
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<td>80</td>
<td>44.91</td>
<td>14.72</td>
<td>14.98</td>
<td>14.98</td>
<td>-895.5</td>
<td>2.79E+07</td>
<td>7.80E+07</td>
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<tr>
<td>85</td>
<td>42.07</td>
<td>15.11</td>
<td>15.19</td>
<td>15.19</td>
<td>-938.3</td>
<td>2.75E+07</td>
<td>8.21E+07</td>
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<tr>
<td>90</td>
<td>39.43</td>
<td>15.09</td>
<td>15.27</td>
<td>15.27</td>
<td>-978.2</td>
<td>2.71E+07</td>
<td>8.72E+07</td>
</tr>
<tr>
<td>95</td>
<td>36.97</td>
<td>15.18</td>
<td>15.24</td>
<td>15.24</td>
<td>-1016</td>
<td>2.67E+07</td>
<td>9.13E+07</td>
</tr>
<tr>
<td>100</td>
<td>34.71</td>
<td>15.15</td>
<td>15.12</td>
<td>15.12</td>
<td>-1051</td>
<td>2.63E+07</td>
<td>9.53E+07</td>
</tr>
<tr>
<td>105</td>
<td>32.61</td>
<td>15.26</td>
<td>14.94</td>
<td>14.94</td>
<td>-710.8</td>
<td>3.57E+07</td>
<td>-1.38E+11</td>
</tr>
<tr>
<td>110</td>
<td>30.63</td>
<td>16.47</td>
<td>14.69</td>
<td>14.69</td>
<td>-1115</td>
<td>2.57E+07</td>
<td>1.02E+08</td>
</tr>
<tr>
<td>120</td>
<td>27.02</td>
<td>14.77</td>
<td>14.02</td>
<td>14.02</td>
<td>-1172</td>
<td>2.50E+07</td>
<td>1.08E+08</td>
</tr>
<tr>
<td>125</td>
<td>25.34</td>
<td>14.68</td>
<td>13.57</td>
<td>13.57</td>
<td>-1199</td>
<td>2.48E+07</td>
<td>1.19E+08</td>
</tr>
</tbody>
</table>
From the power stats in the above table, at about after 20A of GIC injection, the distortion levels shoot up rapidly indicating that the core is completely saturated with excess flux. At this point, we also see a decrease in Active Power is attributed to increasing losses due to heat formation, displaced flux which implies depreciating efficiency of the transformer.

Figure 6.2 depicts saturation characteristics with step wise increase in GIC injection with an increase of 15 A per step. The Flux-Current magnetisation curve is biased to one side

In the Figure 6.3, we see the difference in exciting current waveforms at rated conditions and when the transformer is in a saturated state. The magnitude of $I_{exc}$ increases manifold with saturation of the core inciting harmonic components in the current waveform. An increasing trend in THD is also witnessed in the waveforms.
Figure 6.2 Saturation characteristic distortion with increasing GIC Injection
Figure 6.3  Deterioration of Excitation current $I_{exc}$ with GIC injection
6.2 RESULTS FROM GRID AND VOLTAGE STABILITY ANALYSIS

The test case system was subjected to three different intensities of a geomagnetic storm as represented in the following results and are discussed in detail.

a) Operating point ‘A’ (E=0 V/km)

>> Jacobian
1 65.34
2 39.95
3 21.98
4 18.92
5 16.43
6 2.71
7 5.57
8 7.66
9 11.34

Critical mode of the system is 6th eigen value 2.706

Participation factors of buses corresponding to the critical mode
1 0.000
2 -0.000
3 -0.000
4 0.008
5 0.004
6 -0.000
7 0.070
8 -0.000
9 0.200
10 0.239
11 0.111
12 0.019
13 0.032
14 0.316

The ranking of the buses in order of their participation factors are
14
10
9
11
7
13
12
4
5
1
2
3
6
8

The critical bus of the system is 14th bus with participation factor 0.316
Figure 6.4 Test case at operating point ‘A’
Figure 6.5 Q-V curve of the critical bus-Bus 14 at operating point ‘A’

Table 6.2 Results from QV curve Analysis for Operating point ‘A’

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>V at Q0</th>
<th>Q0</th>
<th>Q_{inj,0}</th>
<th>V_{max}</th>
<th>Q at V_{Max}</th>
<th>Q_{inj} at V_{max}</th>
<th>V at Q_{min}</th>
<th>Q_{min}</th>
<th>Q_{inj, min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1.04</td>
<td>0.00</td>
<td>0.00</td>
<td>1.1000</td>
<td>32.27</td>
<td>32.27</td>
<td>0.5855</td>
<td>-70.46</td>
<td>-70.46</td>
</tr>
</tbody>
</table>
Figure 6.4 represents the test case at a chosen operating point ‘A’ succeeded by its respective modal analysis simulation results. Bus 14 is identified to be the critical bus with a participation factor ‘.316’ followed by the remaining load buses. It is to be noted that at this standpoint, only load buses are somewhat prone to voltage instability whereas the remaining PV buses and swing bus possess a null participation factor indicating their stability.

Subsequently, the QV curve of Bus 14 (Figure 6.5) was generated as the main effect of GIC was conveyed as loss in reactive power. The Q-V curve was then generated to see if the bus has a stable operating point and to evaluate its Reactive Power Margin (RPM).

Table 6.2 contains data of the generated Q-V curve of the bus 14 at this operating point with a RPM of 70.46 MVar.
b) Operating point ‘B’ (E=5V/km)

>> Jacobian
1 49.44
2 33.81
3 27.69
4 21.29
5 16.48
6 13.58
7 11.83
8 0.49
9 8.67
10 2.25
11 5.28
12 4.50
13 4.09

Critical mode of the system is 8th eigen value 0.487
Participation factors of buses corresponding to the critical mode
1 0.000
2 0.003
3 0.009
4 0.016
5 0.014
6 0.099
7 0.063
8 0.059
9 0.096
10 0.114
11 0.122
12 0.135
13 0.129
14 0.140

The ranking of the buses in order of their participation factors are
14
12
13
11
10
6
9
7
8
4
5
3
2
1

The critical bus of the system is 14th bus with participation factor 0.140
Figure 6.6 Test case at operating point ‘B’
Figure 6.7 Q-V curve of the critical bus-Bus 14 at ‘B’

Table 6.3 Results from QV curve Analysis for Operating point ‘B’

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>V at Q0</th>
<th>Q0</th>
<th>Q_{inj_0}</th>
<th>V_{max}</th>
<th>Q at V_{Max}</th>
<th>Q_{inj at V_{max}}</th>
<th>V at Q_{min}</th>
<th>Q_{min}</th>
<th>Q_{inj_min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.92</td>
<td>0</td>
<td>0</td>
<td>1.1</td>
<td>52.92</td>
<td>52.92</td>
<td>0.4967</td>
<td>-48.9</td>
<td>-48.9</td>
</tr>
</tbody>
</table>
Figure 6.6 represents the test case at a chosen operating point ‘A’ succeeded by its respective modal analysis simulation results. Bus 14 is identified to be the critical bus with a participation factor ‘. 140’ followed by the remaining load buses. It is to be noted that at this standpoint, not only load buses, but all other buses except Bus 1 (swing bus) also have a non-zero participation factor due to their instability.

Subsequently, the QV curve of Bus 14 (Figure 6.7) was generated to see if the bus has a stable operating point and to evaluate its Reactive Power Margin (RPM). Compared to the previous operating point, there is a pronounced decrease in the RPM of the critical most bus i.e., Bus 14 from 70.46 MVar to 48.9 MVar due to the loss of reactive power.

Even though the bus has a stable operating point at this instant, it is well beneath its normally accepting limit and also suffers a loss in reactive power. To bring the bus voltage levels within the acceptable limits 0.95 pu and 1.05 pu, there needs to be an additional injection of reactive power.

At this point, several transformers and transmission lines indicated in red are beyond their normal operating limits which indicates this to be an unstable operating point.
c) Operating Point ‘C’ (E=9.5 V/km)

```matlab
>> Jacobian
1 41.15
2 31.27
3 21.66
4 17.51
5 13.58
6 11.38
7 9.78
8 6.99
9 0.52
10 5.10
11 3.64
12 3.39
13 1.96
```

Critical mode of the system is 9th eigen value 0.519
Participation factors of buses corresponding to the critical mode
```
1 -0.000
2 0.001
3 0.005
4 0.011
5 0.010
6 0.100
7 0.056
8 0.048
9 0.095
10 0.117
11 0.129
12 0.145
13 0.136
14 0.148
```

The ranking of the buses in order of their participation factors are
```
14
12
13
11
10
6
9
7
8
4
5
3
2
1
```

The critical bus of the system is 14th bus with participation factor 0.148
Figure 6.8 Test case at operating point ‘C’
Figure 6.9 Q-V curve of the critical bus-Bus 14 at operating point ‘C’

Table 6.4  Results from QV curve Analysis for Operating point ‘C’

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>V at Q0</th>
<th>Q0</th>
<th>inj 0</th>
<th>V_max</th>
<th>Q at V_max</th>
<th>inj at V_max</th>
<th>V at Q_min</th>
<th>Q_min</th>
<th>inj_min</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.37</td>
<td>0</td>
<td>0</td>
<td>1.1</td>
<td>207.63</td>
<td>207.63</td>
<td>0.3521</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 6.8 represents the test case at a chosen operating point ‘A’ succeeded by its respective modal analysis simulation results. Bus 14 is identified to be the critical bus with a participation factor ‘0.146’ followed by the remaining load buses. It is to be noted that at this standpoint, all the load buses are somewhat prone to voltage instability except Bus 1 (swing bus) possess a non-zero participation factor indicating their stability.

Subsequently, the QV curve of Bus 14 (Figure 6.9) was generated as the main effect of GIC was conveyed as loss in reactive power. The Q-V curve was then generated to see if the bus has a stable operating point and to evaluate its Reactive Power Margin (RPM).

The results shown above show that, with increase in the intensity of the geomagnetic storm, the voltage levels drop considerably which are depicted by the voltage contours. The number of buses which participate in voltage collapse also increases signifying the spread of voltage disturbances if they are left unmitigated.

Also, the components of the system such as transformers and transmission lines are required to function beyond their rated limits which will stress the system and restrict power transfer to the load areas. Persistent low voltage levels are hazardous to power system assets.

From the Q-V curves, it was observed that there is a drastic decline in the Reactive Power Margin (RPM) stresses the system and pushes the grid towards voltage collapse which confirms the hypothesis discussed in earlier chapters.
6.3 EVALUATION OF CONTINGENCIES

Observations from the earlier sections indicate the possible contingencies confronted by the system operators. Contingencies can be defined as events that are likely to occur. With respect to power system operation, they can be referred to as the outage of specific power system assets caused by a disturbance. Contingencies normally encountered are the failure of transformers, collapse of buses due to under voltage and tripping of transmission lines which lead to power transfer disruption in the transmission grid. Contingency analysis tool is an important step because it is a crucial step in simulating the outcomes of problems in a power system. It is mainly used off-line to study the impact of power system malfunction on normal operation. It also gives power system operators the facility to identify future outages and be informed to deal with such disturbances by evolving effective contingency plans.

The Contingency Analysis tool in PowerWorld Simulator was used to analyze the effect of the possibility of loss/outage of power system assets due to a geomagnetic storm. The critical bus i.e. Bus 14 and two other transformers were power system elements that were observed to be prone to collapse due to the onset of geomagnetic phenomena.

The constraints used were:

Transformers : 90% Rated MVA.

Buses : 0.90 Voltage p.u magnitude.

Transmission Lines : 95% Capacity of their rated limits.
### Table 6.5 Contingency evaluation at Operating point ‘A’

<table>
<thead>
<tr>
<th>Label</th>
<th>Skip</th>
<th>Processed</th>
<th>Solved</th>
<th>Islanded Load</th>
<th>Violations</th>
<th>Max Branch %</th>
<th>Min Volt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Bus 14 Collapse</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xfmr 5-6 failure</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xfmr 4-9 failure</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 6.6 Contingency evaluation at Operating point ‘B’

<table>
<thead>
<tr>
<th>Label</th>
<th>Skip</th>
<th>Processed</th>
<th>Solved</th>
<th>Islanded Load</th>
<th>Violations</th>
<th>Max Branch %</th>
<th>Min Volt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Bus 14 Collapse</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>3</td>
<td>163.6</td>
<td></td>
</tr>
<tr>
<td>Xfmr 5-6 failure</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>2</td>
<td>171.1</td>
<td></td>
</tr>
<tr>
<td>Xfmr 4-9 failure</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>1</td>
<td>176.5</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6.7 Contingency evaluation at Operating point ‘C’

<table>
<thead>
<tr>
<th>Label</th>
<th>Skip</th>
<th>Processed</th>
<th>Solved</th>
<th>Islanded Load</th>
<th>Violations</th>
<th>Max Branch %</th>
<th>Min Volt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Bus 14 Collapse</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>14</td>
<td>241.6</td>
<td>0.822</td>
</tr>
<tr>
<td>Xfmr 5-6 failure</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>9</td>
<td>257.5</td>
<td>0.846</td>
</tr>
<tr>
<td>Xfmr 4-9 failure</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>12</td>
<td>245.5</td>
<td>0.828</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Category</th>
<th>Element</th>
<th>Value</th>
<th>Limit</th>
<th>Percent</th>
<th>Area Name Assoc</th>
<th>Nom kW Assoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Branch MVA</td>
<td>Bus 5 ( 5) -&gt; Bus 4 ( 4)</td>
<td>104.27</td>
<td>100.00</td>
<td>104.27</td>
<td>IEEE14-IEEE14</td>
<td>69.0</td>
</tr>
<tr>
<td>2 Branch MVA</td>
<td>Bus 4 ( 4) -&gt; Bus 3 ( 3)</td>
<td>85.57</td>
<td>50.00</td>
<td>171.13</td>
<td>IEEE14-IEEE14</td>
<td>69.0</td>
</tr>
<tr>
<td>3 Branch MVA</td>
<td>Bus 5 ( 5) -&gt; Bus 6 ( 6)</td>
<td>84.82</td>
<td>50.00</td>
<td>156.04</td>
<td>IEEE14-IEEE14</td>
<td>69.0</td>
</tr>
<tr>
<td>4 Bus Low Volts</td>
<td>Bus 3 ( 3)</td>
<td>0.88</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>69.0</td>
</tr>
<tr>
<td>5 Bus Low Volts</td>
<td>Bus 4 ( 4)</td>
<td>0.82</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>69.0</td>
</tr>
<tr>
<td>6 Bus Low Volts</td>
<td>Bus 5 ( 5)</td>
<td>0.85</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>69.0</td>
</tr>
<tr>
<td>7 Bus Low Volts</td>
<td>Bus 6 ( 6)</td>
<td>0.90</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>8 Bus Low Volts</td>
<td>Bus 7 ( 7)</td>
<td>0.84</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>9 Bus Low Volts</td>
<td>Bus 8 ( 8)</td>
<td>0.84</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>10 Bus Low Volts</td>
<td>Bus 9 ( 9)</td>
<td>0.84</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>11 Bus Low Volts</td>
<td>Bus 10 (10)</td>
<td>0.84</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>12 Bus Low Volts</td>
<td>Bus 11 (11)</td>
<td>0.85</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>13 Bus Low Volts</td>
<td>Bus 12 (12)</td>
<td>0.88</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
<tr>
<td>14 Bus Low Volts</td>
<td>Bus 13 (13)</td>
<td>0.88</td>
<td>0.90</td>
<td></td>
<td>IEEE14</td>
<td>13.8</td>
</tr>
</tbody>
</table>
With increasing intensities of geomagnetic storms represented by the three test cases A, B and C, the violations such as transmission lines getting overloaded under voltage buses add up leading to large scale simultaneous disruption of power at different regions of the system. Tables 6.5, 6.6 and 6.7 show the impact of each of three tested contingencies have on the rest of the system.

In this case, the measures that can be suggested to prevent total system collapse such as:

- Provide reactive power support at the critical bus i.e., Bus 14 to prevent its collapse. This was achieved by hooking up a synchronous condenser at bus 14 and bringing it.
- Re-route power to other load buses by taking transformers between Buses 5 & 6 and Buses 4 & 9 out of service temporarily as their VAR consumption increases at the onset of the geomagnetic event.

After implementing these measures on the system, it was observed that the system (Refer Fig 6.10) achieves voltage stability with all the buses well beyond their minimum limit and no overloaded transmission lines were observed unlike earlier.

Similarly, depending on situational necessity and intensity of the geomagnetic intensity, contingency plans can be developed based upon prior analysis results in a step wise manner to ensure timely response and prevent possible widespread power outage and equipment damage thereby suppressing propagation of any further effects into the grid and the load.
Figure 6.10 Test Case with Contingency Plan
CHAPTER 7: CONCLUSION AND SCOPE FOR FUTURE WORK

This thesis intends to raise the issue of geomagnetic phenomenon as a potential disturbance to the bulk power system. A systematic approach was adopted in bringing the issue forward in a suitable manner. This was achieved by studying the internal sequence of events that give rise to GIC. The next step was to quantify the issue and represent it in the system whilst also examining several other methods that have been previously used.

PowerWorld Simulator was adopted to simulate GIC into the standard IEEE 14 bus system. The effect of GIC on a single component on the power system viz., High Voltage Transformer was assessed. Simulink was used to model the transformer and explain the effects due to the entry of GIC into the transformer. The results were taken into perspective and then extended to a standard IEEE 14 bus system. The simultaneous loss of reactive power and harmonic injection into the system causes low voltage levels leading the system towards collapse. Voltage stability is an important issue which was studied and analyzed during a GIC storm. A method called Modal Analysis was utilized to study the voltage stability of the system and the most critical and vulnerable buses in the system were identified and ranked in terms of their proximity to voltage collapse.

The participation factors of all the buses are observed and ranked in order their magnitude which represents their likelihood to undergo voltage collapse. The bus which had the highest participation factor was chosen and its Q-V cure was generated to illustrate the loss in reactive power due to GIC circulation in the grid.
Some important conclusions that can be drawn from this thesis are:

- **Geomagnetically Induced Currents** are a credible threat to the bulk power system and should be appropriately analyzed and incorporated as a constraint while designing the system. An industry standard procedure needs to be developed in dealing Geomagnetic Disturbance like all other natural calamities. Utility wide GIC monitoring is suggested to enhance quick response to any disturbances.

- **Steady state Power System Analysis** has been performed before and after a contingency to observe if all active and reactive power generation limits, bus voltage magnitude limits, transformer and transmission line loading limits is abided by. The threshold limit of operational stress during such disturbances can also be approximated by suitable analysis.

- It is very essential to investigate and analyze the effects of a GIC over a system component viz., Transformers, Generators so that suitable mitigation measures can be devised. Various possible GMD scenarios have to be tested to see if they can endure the stresses impinged upon them. The necessity of advanced tools for vulnerability assessments has been demonstrated.

- **Dynamic Cable Rating (DCR)** and series compensation of transmission lines has to be extensively put into practice in regions prone to such disturbances to combat GIC effects such as sudden loss in line limits and power transfer capability.

- Installation of mitigation devices such as neutral resistances and capacitors in neutrals of grounded transformers to obstruct GIC flow into the system.
• NERC has recently reviewed several commercial GIC reducing/blocking devices to serve as a guide for system planners to choose the optimum device basing on the transformers technical specifications and configuration [39].

• Equipment design specifications have to be inspected for necessary improvements and a base case criterion has to be established which can be incorporated in the manufacturing process.

• Reactive power producing components should be located as close as possible to the critical buses in the system. After sufficient research, it is opined that Synchronous condensers are to be preferred to produce the necessary MVar to maintain voltage levels since they are known to be absorptive of harmonic components and are quite stable during power swings in the system.

As a possible extension to this thesis, similar analyses can be performed with real data obtained from utilities. Models for GIC blocking devices can be developed, simulated, tested and validated. More field research is suggested to understand how these devices react to a geomagnetic disturbance. A contingency plan can be formulated basing on the results to protect the assets in the system from GIC effects, keeping the current waveform distortion within limits, preserving a stable operating point and maintaining the reliability.
A. Function for Modal Analysis and Jacobian operation.

function []= modal(Jac)

% This function takes the Power flow Jacobian ‘Jac’ generated from the PowerWorld Simulator as input and performs Modal analysis operations on it.

% The eigen vectors and eigen values are calculated and subsequently, the participation factors of buses in voltage collapse in the critical mode of the system are determined and ranked in order.

m=length(Jac);
reshape(Jac,m,m);
Y=mat2cell(Jac,[m/2,m/2],[m/2,m/2]);

%Calculation of Reduced Jacobian Matrix J.
J= Y{2,2}-(Y{2,1}/(Y{1,1})*Y{1,2});
J=full(J);

%Eigen value & Eigen vector calculation.
[V,D]=eig(J);
Vl=(inv(V'))';
n=length(J);
eigJ=eig(J);

newLength=0;
for k=1:n
    if(eigJ(k) ~= 1)
        fprintf('%d %3.2f
',k, eigJ(k));
        newLength=newLength+1;
    end
end

[C,I]=min(eigJ(1:newLength));
fprintf("n Critical mode of the system is %d th eigen value %3.3f
",I,C);
P=zeros;

for k=1:n
    for i=1:n
        % Participation factor of bus k to mode i :
P(k,i)=V(k,i)*Vl(i,k);
    end
end

%Participation factors corresponding to the weakest mode:
[PF]=P(:,I);

display('Participation factors of buses corresponding to the critical mode');

for j=1:length(PF)
    fprintf('%d %3.3f
',j,PF(j));
end

[R,IX]=sort(PF,'descend');

fprintf('
 The ranking of the buses in order of their participation factors are
');

fprintf('%d
',IX);

[W,I]=max(PF);fprintf('
 The critical bus of the system is %d th bus with participation factor %3.3f
',I,W);

end
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VITA

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In August 2011, he enrolled as a MSEE student in the Department of Electrical and Computer Engineering at the University of Kentucky. In April 2013, he was qualified as an Engineer in Training (FE) by the National Council of Examiners for Engineering and Surveying (NCEES).

He currently works as a Power Systems Engineer in the Power Systems Engineering Division of Schneider Electric Inc., at Lexington, Kentucky.