Sudan University of Science and Technology

College of Graduate Studies

Effect of Geomagnetic Disturbances on Electric Transformers Located at a Geomagnetic Low Latitude

أثر الإضطرابات الجيومغناطيسية علي محولات الكهرباء عند خط عرض مغناطيسي منخفض

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree

Of Master in Physics

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Dedication

This thesis is dedicated to the sake of Allah, my creator, and my master, my great teacher, and messenger, Mohammed (May Allah bless and grant him), who taught us the purpose of life, my parents, my beloved brothers, and sisters. To all my family, the symbol of love and giving, my friends who encourage and support me, all the people in my life who touch my heart.

Acknowledgement

First I would like to thank my supervisor, **Dr. Magdi Elfadil Yousif**, for all the help and tips I got while working on the dissertation. I would also like to thank **Eng.Faize Alameer** and **Eng. Hassan Mahmoud** for their collaboration and providing us by the data, I would also like to thank my friends and family for their love and support, without which this accomplishment would not have been achievable.

Abstract

Space weather has been a task of research in modern fields of science; therefore, our recent technology is certainly influenced by impact of space weather particularly in satellites, spaceborne systems. Moreover, space weather has impacts on ground based technology such as electric power system, pipeline, and railways. Space weather variations can cause geomagnetically induced currents penetrate conducting structures of the transformers and cause: half-cycle saturation, increase the reactive power consumption, high levels of harmonics and heating. This could possibly leads to occurrence of blackouts and losses of power production.

In the current thesis, we investigate a correspondence occurrence of blackout in Sudan national power grid which Located at geomagnetic low latitude with space weather variations. Data from a transform in the grid were collected whence winding current, voltage and winding temperature one day including a time of blackout were checked in correspond to the geomagnetic storm time. Results of the investigated data showed that: the winding current was increased almost 5-hours before onset of the blackout, meanwhile, the voltage was almost steady in the same period before blackout. Moreover, the winding temperature was increased almost 2-hours before blackout and continued to increase to some peak which was centered on blackout period. Another feature that the winding current increased after blackouts while the voltage still steady almost after blackout. The geomagnetic equatorial disturbance storm index, namely, Dst showed a corresponding minor storm during occurrence of blackout, for the onset was found to correspond recovery phase of that storm. These results interpret the possible contribution of space weather effects on the stability of the national power grid.

المستخلص

أصبح طقس الفضاء من أهم العلوم الحديثه التي تهتم بدراسه التغيرات في الفضاء وثأتيرها علي الأرض حيث أنه يؤثر علي أنظمه تكنولوجيا الفضاء الحديثه مثل الأقمار الإصطناعيه, وعلاوه علي ذلك يؤثر طقس الفضاء علي أنظمه التكنولوجيا الأرضيه مثل أنابيب البترول ,خطوط السكك الحديديه وشبكه الكهرباء .التغيرات في طقس الفضاء قد تسبب تياراً مستحثاً جيومغناطيسياً يخترق هياكل المحولات ويتسبب في : تشبع نصف الدوره في قلب المحول ، وكذلك زيادة استهلاك الطاقة التفاعلية، مما يؤدي إلي زياده مستوي الذبذبات في موجة التيار وبالتالي تسخين المحول الذي بدوره يقود إلى إحتماليه حدوث إنقطاع تام للتيار الكهربائي وفقدان الطاقة الكهربائيه.

في هذه الأطروحة تم التحقق من التزامن بين حدوث إنقطاع للكهرباء بالشبكه القوميه للكهرباء والتي تقع عند خط عرض مغناطيسي منخفض والتغيرات في الطقس الفضائي. تم جمع بالسودان بيانات كل من التيار, الجهد ودرجة الحرارة من محول بالشبكة القومية ليوم كامل تتضمن زمن حدوث إنقطاع للكهرباء وتم مطابقتها مع مؤشر العواصف الجيومغناطيسيه في ذلك اليوم. وقد أظهرت نتائج البيانات أن التيار المار في ملف المحول إزداد قبل خمس ساعات تقريبا من بداية الإنقطاع التام للتيار، بينما كان الجهد ثابتا تقريبا في نفس الفترة . وعلاوة على ذلك إزدادت درجة حرارة الملف قبل ساعتين تقريبا من الإنقطاع وإستمرت في الارتفاع حتي وصلت ذروتها التي تركزت في فترة الإنقطاع التام للتيارالكهربائي , ولوحظ أيضا أن التيار إزداد تدريجيا بعد فترة الإضطرابات الإنقطاع في حين أن الجهد مازال مستقراً في نفس الفترة. وقد أظهرت ملاحظات مؤشر الجيومغناطيسة الإستوائية تزامناً لحدوث عاصفة جيومغناطيسية ثانوية في فترة حدوث الإنقطاع التام للتيار الذي حدث في طور العودة الي ماقبل العاصفه. وتفسر هذه النتائج الإسهام المحتمل لآثار الطقس الفضائي على إستقرار شبكة الكهرباء القومية.

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List of Abbreviations

AC	Alternative Current
CME	Coronal Mass Ejections
DC	Direct Current
Dst	Disturbance amplitude storm time
EMF	Electromagnetic Force
GIC	Geomagnetically Induced Current
GMDs	Geomagnetic Disturbances
GPS	Global Positioning System
IAGA	International Association of Geomagnetism and Aeronomy
MVAR	Mega volt-Ampere Reactive
MW	Mega Watt
NOAA	National Oceanic and Atmospheric Administration
NRBD	Neutral Resistor/Blocking Device
Pc	Continuous pulsations
Pi	Irregular pulsations
SPE	Solar Proton Events
THD	Total Harmonic Distortion
ULF	Ultra-low frequency
UTC	Coordinated Universal Time
UV	Ultraviolet radiation
VAR	Volt-Ampere Reactive
WAAS	Wide Area Augmentation System

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Chapter One

Introduction

1.1 Introduction

Space weather is a natural phenomenon associated with solar activity. This activity is manifested in the form of energy releases such as solar flares, coronal mass ejections (CMEs), and high-energetic particles. These ejections are spread through the interplanetary space called solar wind, this solar wind affects the space technology and might cause destructive damage to satellites, spacecraft and even astronauts may be affected by exposure to high doses of radiation.

When the solar wind reaches the ground and interacts with the earth’s magnetosphere it causes magnetic disturbances and leads to geomagnetic activity, such as geomagnetic storms, sub storms, aurora and geomagnetic pulsations and hence, drive geoelectric currents on the ground called Geomagnetically Induced Current GIC which has significant effects on the ground based technology such as oil pipelines, railways, and the electric power grid transformers.

The flows of induced GIC through power grid transformers can cause short and long term impacts lead to damage and failure in transformers functionality and result in occurrence of blackouts which has been recorded in the history of events around the world.

The effects of the GIC is varies with the magnetic latitude, therefore the GIC have a great influence on the high magnetic latitude regions. But this influence is not confined only on the high magnetic latitudes regions it is also possible to extend to mid and even low magnetic latitudes.

1.2 Research Problem

Geomagnetic disturbances have a number of negative effects on technological systems, power grid is an example. The geomagnetic storms cause GIC penetrates conducting structures of grid transformers. This may cause half-cycle saturation of the

transformer core, which in turn leads to high levels of harmonics in transformer currents, increase transformer reactive power consumption and overheating the transformer. Furthermore, flows of GIC in power transformers can cause malfunction of components with sensitive safety limits and damage the transformer; which finally may lead to blackouts and loss of power production. .
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1.3 Literature Review

In the section some papers addressing similar topics will be presented, in particular, we will highlight the main findings and explain GIC effects on power transformer.

1.3.1. Effects of Geomagnetically Induced Currents on Power Transformers and Power Systems (GIRGIS, et al., 2012)

In this paper, authors have presented the power industry and the true effect of GIC on power transformers. First, they described the phenomenon of part – cycle, semi – saturation of transformer cores due to GIC.The magnitude and wave – shape of the resulting magnetizing current pulse were given for an example of large power transformer when subjected to different levels of GIC. The corresponding harmonics associated with these magnetizing current pulses were also presented (GIRGIS, et al., 2012).

The effects of GIC on the temperature rises in windings and structural parts of a transformer were discussed; typical signatures of GIC associated with Solar Magnetic events were presented.

Based on these measured signatures, calculations were presented in the paper for winding and structural parts hot spot temperature rises due to a representative GIC signature.

One of the most significant contributions of this paper is a detailed description of some of the cases in which power transformers were reported to have suffered damage, or over – heating, during past GIC events which was blamed solely on GIC. Also, actual measurements, made by three major utilities on full size power transformers when subjected to high levels of DC were presented. Also, authors were demonstrate that, because of the nature of the GIC currents, the great majority of power transformers would not experience damaging overheating due to even high levels of GIC. Only transformers with certain design features could suffer some winding damage due to high winding circulating currents when exposed to high levels of GIC.

1.3.2. Analysis Of Geomagnetically Induced Currents At a Low-latitude Region Over The Solar Cycles 23 and 24: Comparison Between Measurements and Calculations (Barbosa1, et al., 2015)

There are an investigation of GIC occurrence in a power network at low latitudes (in the central Brazilian region) during the solar cycles 23 and 24. Calculated and measured GIC data were compared for the most intense geomagnetic storms (i.e. $50 < Dst < 50$ nT) of the solar cycle 24. Results were obtained from this comparison showed a good agreement. The success of the model employed for the calculation of GIC leads to the possibility of determining GIC for events during the solar cycle 23 as well. Calculated GIC in one transformer reached 30A during the ‘‘Halloween storm’’ in 2003whilst most frequent intensities lie below 10A (Barbosa1, et al., 2015). The normalized inverse cumulative frequency for GIC data was calculated for the solar cycle 23 in order to perform a statistical analysis. It was found that a q-exponential distribution fits the calculated GIC frequency distribution for more than 99% of the data. This analysis was provide an overview of the long-term GIC monitoring at low latitudes and suggests new insight into critical phenomena involved in the GIC generation.

1.3.3. Geomagnetically Induced Currents In An Electric Power Transmission System At Low Latitudes In Brazil: A case Study (Trivedi, et al., 2007)

A study of the GIC measurements in Brazil was conducted under a cooperative project between FURNAS (the Brazilian electric power company) and the National Institute for Space Research. During a large geomagnetic storm, which took place on 7-10 November 2004, the GIC amplitudes, measured on the basis of geomagnetic variations in 500 kV power transmission lines in the S-E region of Brazil, were found to be around 15 A (Trivedi, et al., 2007) also the real issue with GIC; namely, the narrow pulse of the magnetizing current which results from part – cycle, core semi – saturation when subjected to high levels of GIC currents was presented.

This one current pulse/cycle causes relays and capacitive components in power systems, to trip causing grid instability. Also, the current pulse was associated with higher order harmonics. As a result, resonance may occur, differential relays may operate, and stability of the grid may be compromised.

1.3.4. Protection of Power Transformers Against Geomagnetically Induced Currents (Gurevich, 2011)

The problem of saturation and failure of power transformers under geomagnetically induced currents and currents of high-altitude nuclear explosions was examined. Also, description of a special protective relay reacting on DC component in the transformer neutral current was showed.

1.4 Objectives of The Study

The objective of this dissertation is to study the effects of geomagnetic disturbances which cause GIC on power grid transformers at geomagnetic low latitude regions considering the space weather phenomenon, the solar activity which leads to geomagnetic disturbances.

1.5 Layout Of The Dissertation

This dissertation is organized in five chapters; one including this chapter. Chapter two discusses the space weather phenomena, through studying the sun, solar cycle and solar activity (solar flare, corona mass ejection, and solar proton events) and the interplanetary between sun and earth, and the geomagnetic disturbances (geomagnetic storms, sub storm, and geomagnetic pulsations).Chapter three discusses the Geomagnetically induced current, the work principle of transformers, the flows of GIC and it effect in transforms also present strategies to mitigate the effect of GIC. Chapter four present the results and discussion.

Chapter five contains a conclusion and recommendation for future work. A list of references used in this research is shown at the end of the thesis.

Chapter Two

Space Weather

2.1 Introduction

Space weather is a very old phenomenon, as old as the sun .It is a consequence of the behavior of the Sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system (Commerce, 2011).

According to the US National Space Weather, "the Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of spaceborne and ground-based technological systems and can endanger human health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socio-economic losses" (Hanslmeier, 2007).

Like the weather, space weather has its roots in the sun. The main distinctions between the two types of weather are where it takes place and the type of energy from the Sun that influences it. For atmospheric weather, we are most concerned with the troposphere, which extends from Earth's surface to the top of the highest clouds at about 10 km(Moldwin, 2008). Space weather science is interested in the space environment around Earth all the way to the Sun. Space begins in a region of Earth's atmosphere called the thermosphere, which starts at roughly 100 km (Hanslmeier, 2007).

The second difference between atmospheric weather and space weather is the type of solar energy that influences the two regions The Sun continuously emits two main types of energy into space – electromagnetic (EM) radiation and corpuscular radiation. The Sun's EM radiation bathes the top of Earth's atmosphere with about1400 watts of power per square meter and heats the lower atmosphere (Moldwin, 2008), surface and oceans unevenly. Winds are driven by these differences in atmospheric temperature. The Sun also continuously emits corpuscular (minute particle) radiation, charged atoms and sub-atomic particles (mostly protons and electrons) in what is called the solar wind. Like winds on

Earth, the solar wind is driven by temperature differences, but those differences are between the Sun's upper atmosphere and interplanetary space (Moldwin, 2008).

2.2 The Sun as the Main Source of Space Weather

We have to start at the Sun, although there are a few other contributions from outer space, the Sun is really the massive source of space weather on Earth. The Sun is an average star, similar to millions of others in the Universe. It is an impressive energy machine. The basic energy source for the Sun is nuclear fusion, which uses the high temperatures and densities within its center to fuse hydrogen, producing energy and creating helium. The Sun has been producing its radiant and thermal energies for the past four or five billion years and will continue to produce energy as it begins its evolution to a white dwarf, in several billion years.

The features on the sun reveal the active and turbulent nature of this highly magnetic, hot gaseous star. sunspots were the first features to be identified on the Sun by man, as they can be seen by the naked eye Galileo made observations in the early 1600's (Center, 2012) recording the spots as they moved from day-to-day; this also showed how the Sun rotated.

2.2.1 The Sun's Structure

The regions of the sun are divided into interior and atmosphere. The interior region is divided into four zones as illustrated in Figure 2.1

The Sun Core: Is a region extends about Rs /4 from the center of the sun, it contains about half of the solar mass; it is great density and high temperature (1.5 × 107K°) (Abd-Allah, 2011) due to the energy tremendous produced from the thermonuclear reaction.

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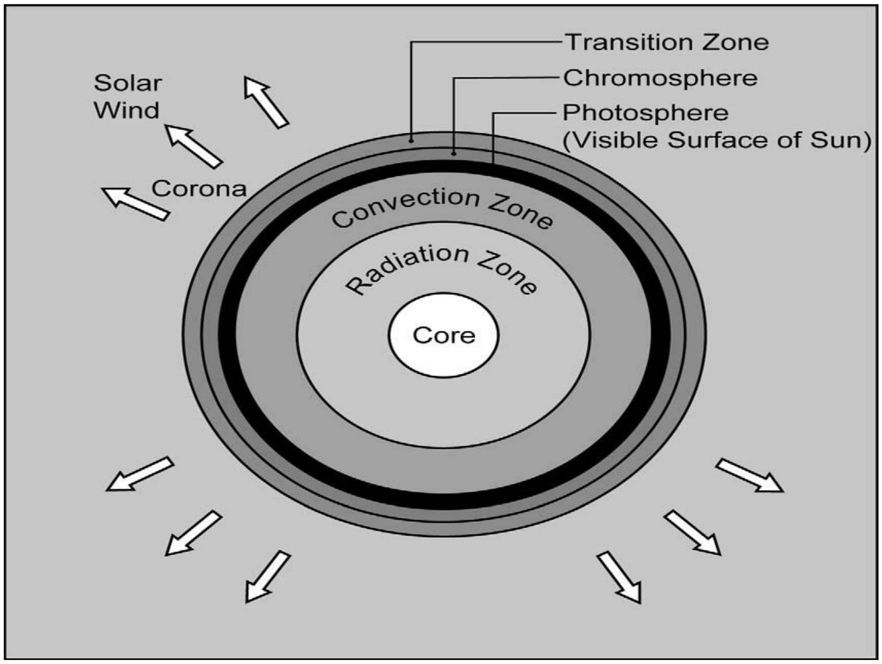

Figure 2.1: the sun layers and zones (Moldwin, 2008)

The Radiative Zone: The transmission of the energy produced in the core to the radiative zone is occurring through gamma-ray diffusion between core radiative zones.

The Convection Zone: This zone is located in the uppermost 30% (Abd-Allah, 2011) of the solar interior. In this region, the solar material is convectively unstable because the radial temperature gradients are large.

The solar atmosphere consists of three layers:

Photosphere: It is the lowest thin and dense (~500 km thick, with densities of about 1023 particles per m^3) (Abd-Allah, 2011) that emits most of the sunlight. The temperature of the photosphere is 5,800K°.

The Chromosphere: The thickness of this layer about 3,000 km and density 1017, $\mathrm{m}^{-3}$where the temperature increases from 4,200K° to ~ 104 K°It is the source region of several transition lines (such UV lines) that are very important in the terrestrial upper atmosphere (Abd-Allah, 2011).

The solar corona: It is the upper most layer, where the temperature increases from ~ 104 K° to ~ 106 K°but there are regions with lower temperature (4000 K°) in which are seen by observers on the Earth as dark sunspots (Abd-Allah, 2011).

2.3 Sunspots and Solar Cycle

On the photosphere, which is the definition of the surface of the Sun, it can be observed groups of dark spots as in figure 2.2. These dark spots are called sunspots and are temporary, during from a few days to a few months. Sunspots can be seen with the naked eye, and are observed as dark compared to the surrounding areas because of the low temperature compared to the rest of the photosphere. The reduced temperature at the sunspots is due to high magnetic fields that counteract the convection preventing hotter material to reach the surface.

The number of sunspots varies with a cycle of 11 years, which is approximately the time of the Sun uses to change polarity. This phenomenon is called the sunspot cycle or the solar cycle. One 11-year cycle is defined as the time between the minimum occurrences of sunspots with changed magnetic polarity. The current solar cycle is the solar cycle 24, being the 24^{th}solar cycle since 1755 (StenOdenwald, 2012). The periodicity of the sunspot cycle is shown in Figure 2.3.

The number of sunspots is strongly related to CMEs, which is the cause of GICs. It is also an indication of the creation of other space weather phenomena such as solar flares and solar proton events (SPE). So, counting of sunspots is still an easy and excellent way to measure the activity of the Sun, even though today there are several modern ways to measure the solar activity.

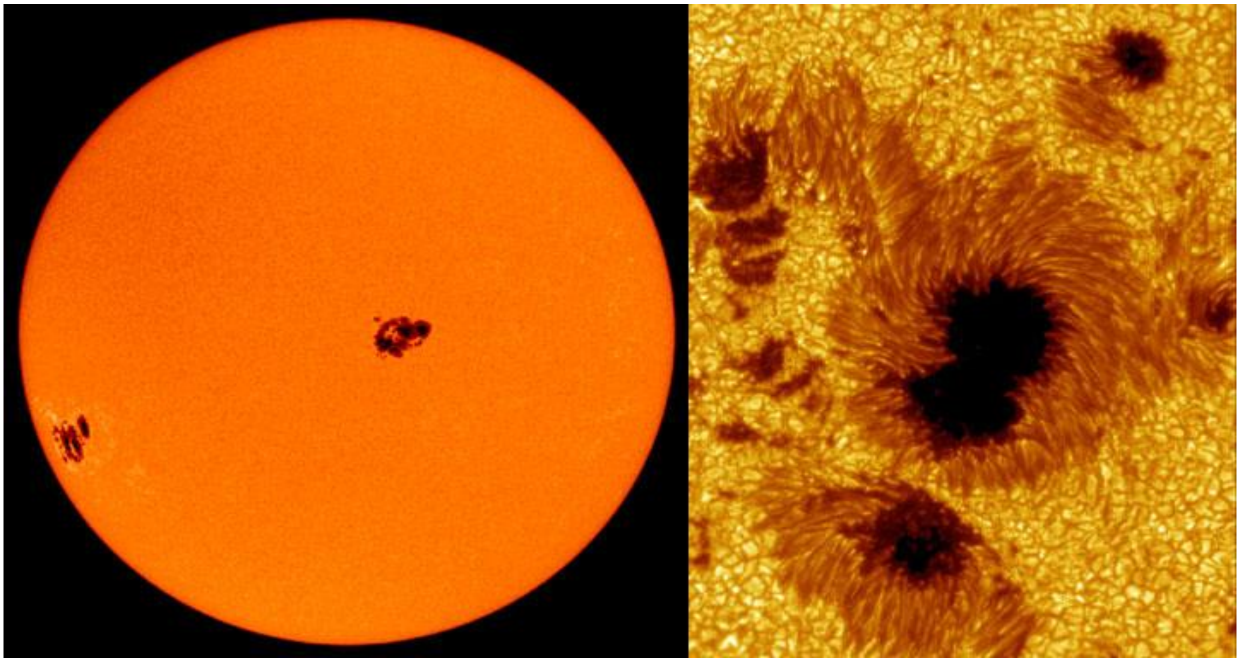

Figure 2.2: the sun spots (Sciences, 1995)

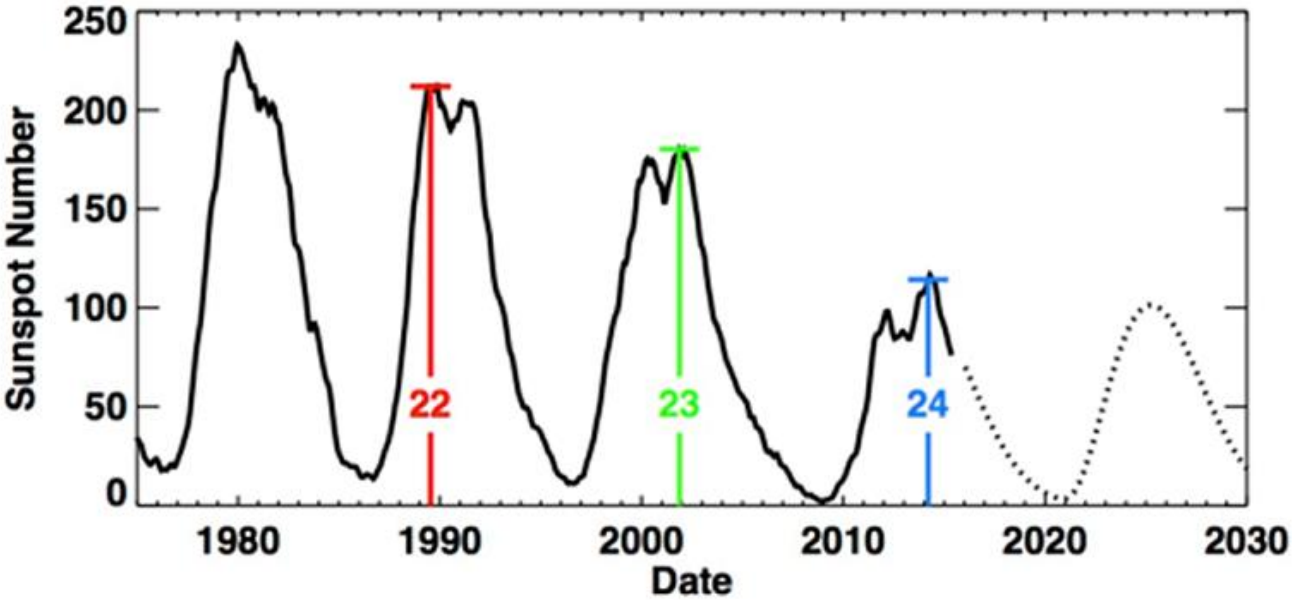

Figure 2.3: the sun spot cycle (Anon., 2017)

2.4 Solar Activities

The solar activity refers to the wide range of transient solar phenomena that vary in complex ways with the solar cycle.

Solar activity is driven by the temporally and spatially varying distribution of magnetic flux in the photosphere, chromosphere, and corona. It covers a range of phenomena for all levels in the solar atmosphere and time-scales ranging.

2.4.1 Solar Flare

Solar flares are intense, short-lived releases of energy shown in figure2.4. They are seen as bright areas on the Sun in optical wavelengths and as bursts of noise in radio wavelengths; they can last from minutes to hours.

Flares are our solar system's largest explosive events. The primary energy source for flares appears to be the tearing and reconnection of strong magnetic fields. They release throughout the electromagnetic spectrum, from gamma rays to x-rays, through visible light out to kilometer-long radio waves (Center, 2012).

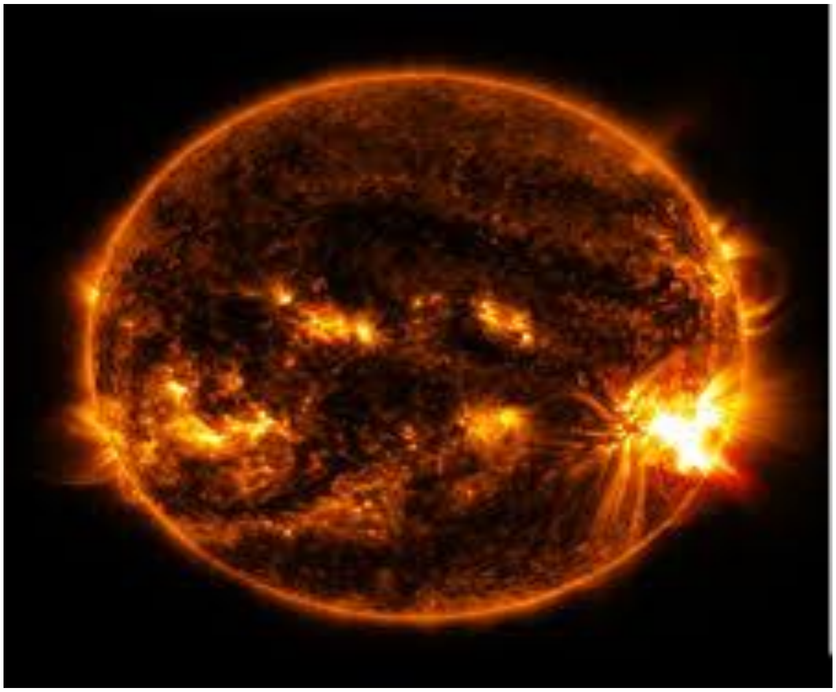

Figure 2.4: show the solar flare (NASA/SDO, 2014)

2.4.2 Coronal Mass Ejection (CME)

The outer solar atmosphere, the corona, is structured by strong magnetic fields. Where these fields are closed, often above sunspot groups, the confined solar atmosphere can suddenly and violently release bubbles or of gas and magnetic fields called coronal mass ejections as shown in figure 2.5. A large CME can contain 1016 grams (a billion tons) of matter that can be accelerated to several million miles per hour in a huge explosion (Center, 2012) solar material streaks out through the interplanetary medium, impacting any planet or spacecraft in its path. CMEs are sometimes associated with flares but usually occur independently.

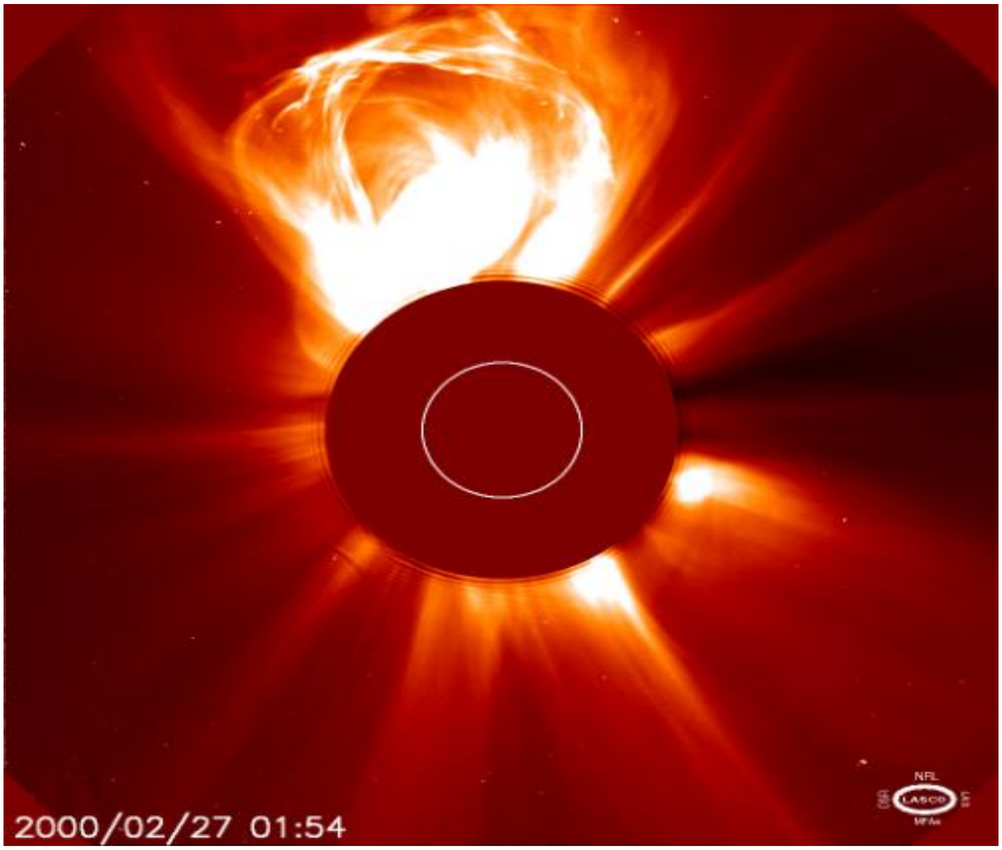

Figure 2.5: the CME eruption ((NASA/ESA), 2000)

2.4.3 Solar Proton Events (SPE)

Solar Proton Events (SPEs) and other energetic particle showers are high energy particles lead to excessive radiation dosages that, over the long term, can accumulate to become a significant hazard. Solar Proton Events (SPEs) can be caused by intense solar flares, but are more commonly related to CMEs withing which intense shock waves can accelerate particles to high energy sooner after ejection by the sun. These particles generally have energies in the range of 10 MeV to 100 MeV (StenOdenwald, 2012).

2.5 The Interplanetary Between Sun and Earth

The region between the Sun and the planets has been termed the interplanetary medium. Although once considered a perfect vacuum, this is actually a turbulent region dominated by the solar wind, which flows at velocities of approximately 250-1000 km/s (about 600,000 to 2,000,000 miles per hour)(Center, 2012). Other characteristics of the solar wind (density, composition, and magnetic field strength, among others) vary with changing conditions on the Sun.

The solar wind flows around obstacles such as planets, but those planets with their own magnetic fields respond in specific ways. Earth’s iron core produces a magnetic field that would look much like the field around a bar magnet. But under the influence of the solar wind, these magnetic field lines are compressed in the sunward direction and stretched out in the downwind direction. This creates the magnetosphere, a complex, teardrop-shaped cavity around Earth. The Van Allen radiation belts are within this cavity, as is the ionosphere, a layer of Earth’s upper atmosphere where photoionization by solar x-rays and extreme ultraviolet rays creates free electrons. The Earth’s magnetic field senses the solar wind, its speed, density, and magnetic field. Because the solar wind varies over time scales as short as seconds, the interface that separates interplanetary space from the magnetosphere is very dynamic. Normally this interface, called the magnetopause, lies at a distance equivalent to about 10 Earth radii in the direction of the Sun. However, during events of higher solar wind density or velocity, the magnetopause can be pushed inward to within 6.6 Earth radii (the altitude of geosynchronous satellites). As the magnetosphere extracts energy from the solar wind, internal processes produce geomagnetic storms (Center, 2012).

2.6 The Geomagnetic Disturbances

The solar wind is a constant stream of charged particles emitted by the Sun; the solar wind force is able to modify the magnetic field of the earth, creating a cavity called the magnetosphere. This cavity shelters the surface of the planet from the high energy charged particles of the solar wind. The outer boundary of the magnetosphere is called the magnetopause as illustrated in figure 2.6. The ejection of plasma is consisting mainly of protons and neutrons. The Earth's magnetic field captures the charged particles approximately 20-40 hours after a flare occurs. A strong change in the Earth's magnetic field results, over a period of approximately five minutes, from the capture of the, energized solar plasma and causes geomagnetic disturbances such as (geomagnetic storms, sub storms, and geomagnetic pulsations). The Sun goes through 11-years solar cycles, with solar activity increasing as the cycle nears its end; that is, the end of the cycle is more violent than the beginning (HUTCHINS., 2012).

2.6.1Geomagnetic Storms

During geomagnetic storms, the magnetic field in the magnetosphere and on the ground is strongly disturbed globally. The perturbation of the magnetic field during a storm is due to the enhancement of the equatorial ring current. This constant but time-dependent westward current consisting mainly of the westward drift of positively charged particles but also the eastward drift of negatively charged particles (onen, 2013).

During storm time the ring current is enhanced and moved spatially closer to the ground. This causes a disturbance in the component of the magnetic field. It can be detected on the ground, as is indeed done at the multiple magnetic observatories. The storms are then classified according to some criteria, most often a specific index calculated from the magnetic measurements of a subset of the observatories. Being global events, the disturbance of the magnetic field during magnetic storms has to be detected by several stations at once to qualify. The most common index to classify the magnitude of the storm is the Dst index. Storms were identified from the Dst index measured by four magnetometers close to the equator (onen, 2013).

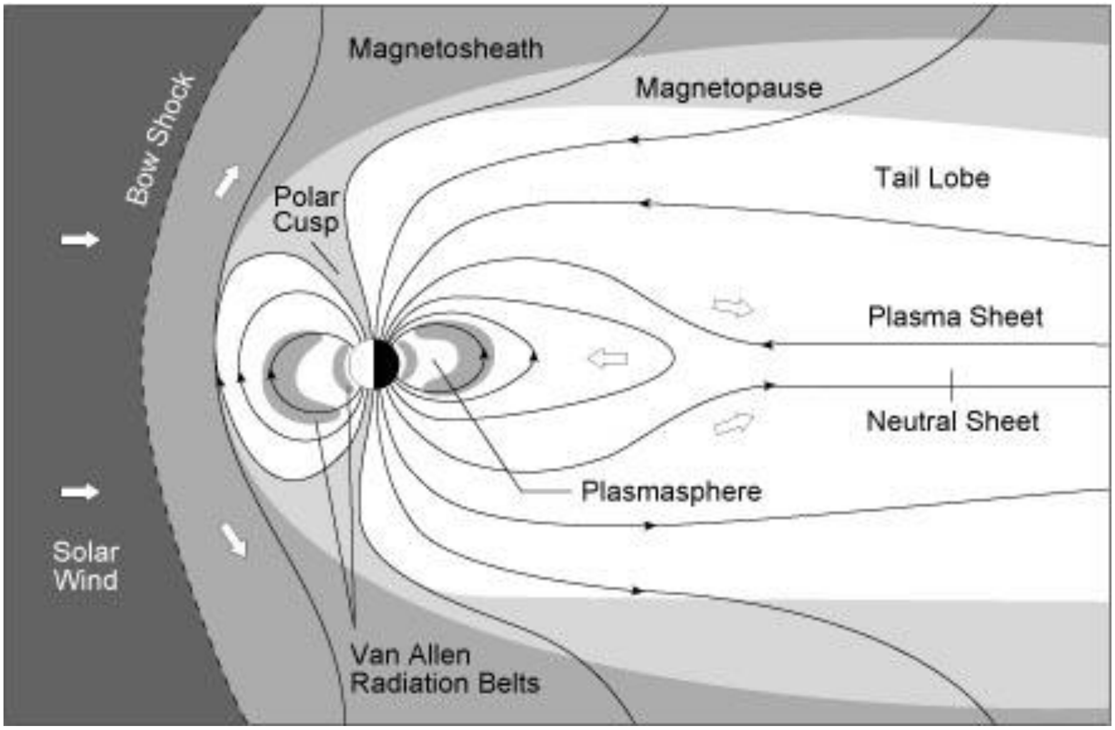

Figure 2.6: the interaction of solar wind with earth magnetosphere (NASA, 2017)

Table 2.1: NOAA Space Weather Scale for Geomagnetic storms (NOAA, 2011).

Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur; some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink, and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required; false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms; long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp=5	1700 per cycle (900 days per cycle)

2.6.2Auroral Sub Storms

Substorms are local phenomena; the substorm growth phase begins with perturbations appearing in the electric and magnetic fields in the polar cap. Around the same time, the field in the lobes starts increasing due to perturbations of cross-tail component of the lobe field. In the near tail, the plasma sheet begins to thin with the magnitude of the field increasing (onen, 2013).

Expansion onset was originally considered the beginning of the sub storm during the rather short expansion phase lasting few tens of minutes, the auroral arcs brighten up and also exhibit a poleward motion. At the same time, the near-Earth plasma sheet thins up to almost nothing, only to start expanding at about ten times the speed of its initial thinning, a result of rapid changes in the cross-tail component of the magnetic field. These fluctuations accompany the sudden appearance of energetic particles. Electro jets in the aurora zone expand northward and westward and there's an intense electron precipitation (onen, 2013).

Finally, the recovery phase, lasting a few hours, starts with the decay of electro jet currents and the recovery of the magnetic field as it was during quiet time configuration, i.e. before the sub storm. The aurora also starts to faint out and they begin to return equatorward to the auroral zone of the quiet time being very numerous, sometimes several sub storms happening during single night, the statistical approach here is more useful when consideringin substorms which are distinct from geomagnetic storms in that the latter takes place over a period of several days, observable from anywhere on earth, injects a large number of ions into the outer radiation belt, and are rare occurrences. Sub storms, on the other hand, take place over a period of a few hours, are observable primarily at the Polar Regions, do not inject many particles into the radiation belt, and are relatively frequent, often occurring only a few hours apart from each other (onen, 2013).

2.6.3 Geomagnetic Pulsations (ULF waves)

Geomagnetic pulsations are short-term (0.2–600 seconds) fluctuations in the geomagnetic field. They are classified into two main types: continuous pulsations (Pc) and irregular pulsations (Pi) and further into seven subtypes, a classification scheme approved by the International Association of Geomagnetism and Aeronomy (IAGA) shown in table 2.2 Pc5 pulsations can readily be studied with data of 140-sec resolution or preferably higher using the methods of Fourier analysis. They can be grouped into two distinct categories by their nature: compressional Pc5 and toroidal Pc5 that is also known as the fundamental mode (onen, 2013).

Table 2.2: classification of geomagnetic pulsations according to Association of Geomagnetism and Aeronomy (IAGA)(Abd-Allah, 2011).

Type	**Notation**	**Period Range (sec)**	**Frequency range (MHz)**
Continuous Pulsations (Pc)	Pc1	0.2-5	200 - 5000
	Pc2	5-10	100 - 200
	Pc3	10-45	22.2 - 100
	Pc4	45-150	6.7 - 22.2
	Pc5	150-600	1.7 - 6.7
	Pc6	> 600	< 1.7
Irregular Pulsations (Pi)	Pi1	1 - 40	25 - 1000
	Pi2	40-150	6.7 - 25
	Pi3	> 150	< 6.7

Chapter Three

The Effect of GIC on Transformers

3.1 Introduction

Through Faraday's law of induction, a changing magnetic field density through a defined area, or a changing flux, results in an induced electromagnetic force. In this case, the resulting EMF is given by a geomagnetic storm interacting with the Earth's magnetic field over an incremental area, inducing geoelectric fields at the Earth's surface and in the ground. The geoelectric fields derive quasi-dc currents in the ground through high voltage transmission lines as in figure 3.1, railway equipment, communication cables, and pipeline networks. The frequency of the current is significantly less than the frequency of the electrical grid, so it is said to be quasi-dc. This current is more commonly known as geomagnetically induced current, or GIC (HUTCHINS., 2012).

GIC is induced into the power grid when a geomagnetic storm interacts with the Earth's magnetic field. This ionospheric interaction has the ability to perturb the auroral electro jets that circulate the Earth's magnetic poles. These circulating electric currents, electrojets, leave their auroral oval when perturbed. The electro jets are extended at increased strength into the lower latitudes, imposing a geoelectric field, as mentioned before. The accumulated voltage difference between two low-impedance ground points in the power grid yields a current high enough to produce documented damage and power system instability to power grids. (HUTCHINS., 2012).

The easiest point of entry for GIC into the electric grid is through the grounded neutral wire of wye connected power transformers. These wires are physically grounded in the earth. These low resistivity wires are the path of least resistance for GIC when compared to the soil. The high voltage neutral connections are an even easier entry for GIC since their resistivity is less than that of the lower voltage transmission lines. Coincidentally, the higher voltage transformers are damaged easier by the excess current flow. The transformers combination of most at risk and most easily damaged is not ideal for the power grid (HUTCHINS., 2012).

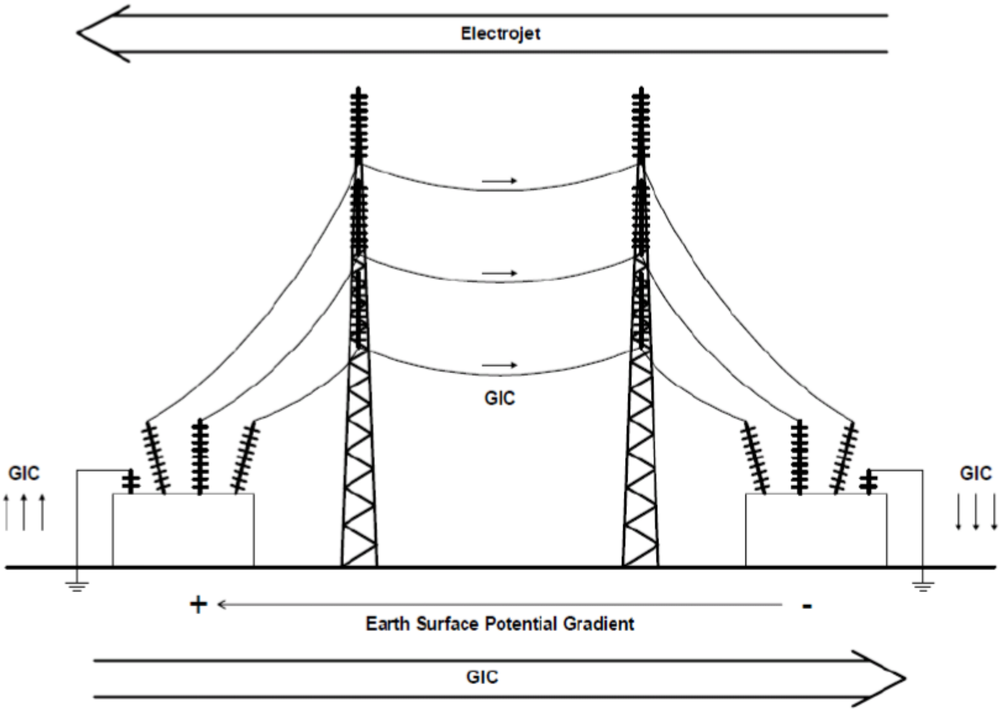

Figure 3.1: the flow of GIC in the transmission lines (Røen, 2016)

3.2 Transformers

The electrical transformer is a static device which transforms electrical energy from one circuit to another without any direct electrical connection and with the help of mutual induction between two windings. It transforms power from one circuit to another without changing its frequency but may beat different voltage level (Group, 2005).

The working principle of transformer depends upon Faraday's law of electromagnetic induction. Actually, mutual induction between two or more winding is responsible for transformation action in an electrical transforme (Group, 2005).

3.2.1 Main Constructional Parts of Transformer

The three main parts of a transformer as shown in Figure 3.2 are:

1. Primary Winding of Transformer- which produces magnetic flux when it is connected to the electrical source.
2. Magnetic Core of Transformer- the magnetic flux produced by the primary winding, that will pass through this low reluctance path linked with secondary winding and create a closed magnetic circuit.
3. Secondary Winding of Transformer- the flux, produced by primary winding, passes through the core, will link with the secondary winding. This winding also wounds on the same core and gives the desired output of the transformer.

3.2.2 The Transformer Work Principle

According to these Faraday's laws, "Rate of change of flux linkage with respect to time is directly proportional to the induced EMF in a conductor or coil".

If we have one winding which is supplied by an alternating electrical source. The alternating current through the winding produces a continually changing flux or alternating flux that surrounds the winding. If any other winding is brought nearer to the previous one, obviously some portion of this flux will link with the second. As this flux is continually changing in its amplitude and direction, there must be a change in flux linkage in the second winding or coil.

According to Faraday's law of electromagnetic induction, there must be an EMF induced in the second. If the circuit of the later winding is closed, there must be a current flowing through it (Group, 2005).

This is the simplest form of the electrical power transformer and this is the most basic of working principle of a transformer. Whenever we apply alternating current to an electric coil, there will be an alternating flux surrounding that coil. Now if we bring another coil near the first one, there will be an alternating flux linkage with that second coil. As the flux is alternating, there will be obviously a rate of change in flux linkage with respect to time in the second coil. Naturally, emf will be induced in it as per Faraday's law of electromagnetic induction. This is the most basic concept of the theory of transformer (Group, 2005).

The winding which takes electrical power from the source is generally known as the primary winding of the transformer. Here in our above example, it is first winding, the winding which gives the desired output voltage due to mutual induction in the transformer is commonly known as the secondary winding of the transformer (Group, 2005).

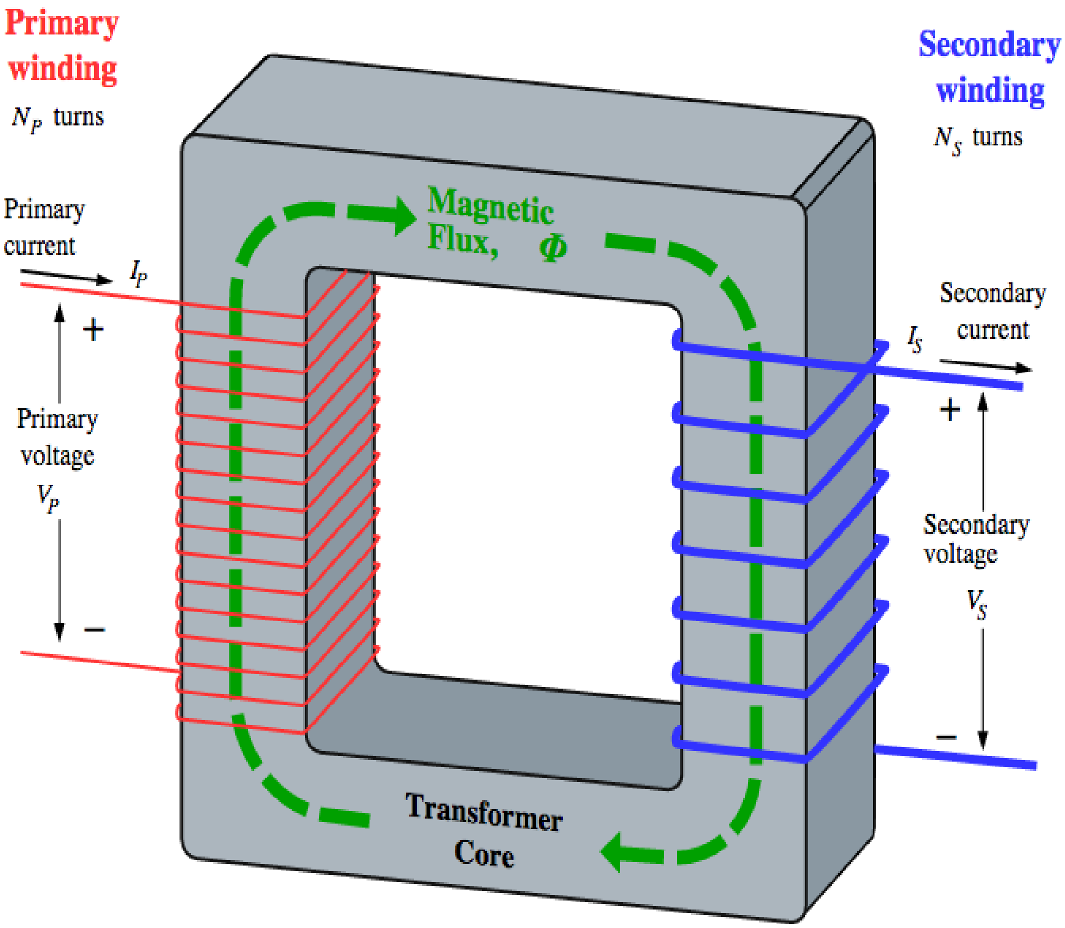

Figure3.2: the transformer construction (Røen, 2016)

3.3 The Flows of GIC on the Power Grid Transformers

GIC is the result of magnetic field induction in the transmission lines. Time varying magnetic fields induces an electric field. The magnitude of the electric field is a function of the earth conductivity structure of the earth, with lower conductivity resulting in higher electric fields.

The resulting field induces a voltage in the transmission line via Faraday's Law

$$\mathrm{V} = \oint \vec{\mathrm{E}}.\,\mathrm{dl} \qquad 3.1$$

Where $\vec{E}$ is a vector representing the electric field, and dl is a vector representing the incremental length and direction of the transmission line for most transmission lines equation 1.3 can be estimated with reasonable accuracy using 3.2

$$\mathrm{V} = \vec{\mathrm{E}}.\{\vec{\mathrm{p}}_2 - \vec{\mathrm{p}}_1\} \qquad 3.2$$

Where, p_1 and p_2 are vectors corresponding to the positions, with respect to a fixed reference, of each end of the line. For GICs to flow in a transmission line, both ends of the transmission line must be connected to grounded transformers.

During a solar storm, the electric field is continuously changing, and hence, not only does the GIC magnitude change continuously but the direction changes as well. For a short transmission line, the total resistance of the GIC path is typically dominated by the winding and ground resistances of the transformers. When the line is short, there may be a little induced voltage.

Conversely, with a long transmission line, the resistance of the phase conductors becomes the dominant resistance, and the induced voltage may be significant ((NERC), 2013).

3.4 The Effects of GIC Flowing in the Transformer

When GIC flows through the high voltage transformers it causes several effects they are:

3.4.1 Short-Term Impacts

Utilities have become experienced in using forecasts to change operating procedures in response to a CME event. Upon learning that a CME event is imminent or receiving telemetry that one already is occurring, a utility or an interconnection can act to reduce their need to transfer large amounts of power.

The degree of reduction that might be possible depends on the way the systems are interconnected, and on the load being served when the event occurs. The problem might not necessarily be worse during peak load periods when it might be a reasonable assumption that all the generators are running anyway, or during light load periods. Also, because the resistivity of the ground under the lines plays a role and cannot be controlled, there may not be any really good options that can be exercised on all occasions (Kirkham & Makarov, 2011).

3.4.2 Long-Term Impacts

Transformers are, with a few exceptions, designed to work with no appreciable DC in the windings. Most large power transformers installed at the ends of high-voltage AC transmission lines would fail if a large DC continues for long enough to heat them appreciably. Transmission operators typically have only a few spare transformers that they can use in emergency situations, so transformer damage or failure can become a problem. Obtaining a replacement transformer, or rewinding a failed unit, is likely to take several months or as much as a year. Smaller devices are known as current transformers, which are used for measuring power-system parameters, also would be adversely impacted. In particular, because of their toroidal construction, current transformers would become permanently magnetized. A process of demagnetization would have to be completed before measurements from the transformer could be trusted. Demagnetization is a manual process that might take an hour or so for each transformer affected, but because there are many current transformers in a power system, the overall process could take several weeks. It is hard to say what the effect would be from operating the power system with saturated current transformers; however, operating the system in this situation might be possible, and probably would be attempted by a utility (Kirkham & Makarov, 2011).

3.4.3 Thermal Effects

GIC flowing in the transformer leads to a higher magnetizing current, which shape produces a higher leakage flux that also contains a lot of harmonics. This leads to a significant increase of eddy and circulating current losses in both windings and structural parts of the transformer, causing heat generation and transformer losses. Because the GIC-imposed thermal duty is outside the standard service parameters the increase in temperature and load losses of windings and structural parts should be assessed individually for each type of power transformer design (Røen, 2016).

3.4.4 Half-Cycle Saturation

When GIC, which are quasi-DC currents, flows in a power transformer, it causes a unidirectional DC flux to flow in the core. As a result, the total flux in the core is the sum of the DC flux and the AC flux, as shown in Equation 3.3. Consequently, in the negative half-cycle, the DC flux will be subtracted from the AC flux and there is no saturation. While in the positive half-cycle the core will go into saturation due to the DC flux, as Shown in Figure 3.3, hence the name half-cycle saturation.

$$\Phi = \Phi_{AC} + \Phi_{DC} \qquad 3.3$$

The magnitude of the DC flux depends on three factors: the magnitude of the induced quasi-DC current, number of turns in the windings where the quasi-DC current flows and the reluctance of the path of the DC flux. This relation is shown in Equation 3.4

$$DC = \frac{N.GIC}{R} \qquad 3.4$$

Where N is the number of turns, GIC is the magnitude of the DC current and R is the reluctance of the magnetic circuit. The reluctance R is found by using Equation 3.2

$$R = \frac{l}{\mu . A} \qquad 3.5$$

Where l the length of the magnetic circuit, µ is the permeability of the material and A is the cross-sectional area of the circuit. Furthermore, the reluctance R is a function of the AC excitation. So, to find the magnitude of the direct flux bias Φ_{DC} one has to take into account the direct flux bias Φ_{DC} dependency of the ac excitation and the level of saturation, and not only the GIC magnitude (Røen, 2016).The significant increase in reactive power consumption due to half-cycle saturation can cause unusual transmission flow of active and reactive power, generator problems due to reactive power limits, and intolerable system voltage depression.

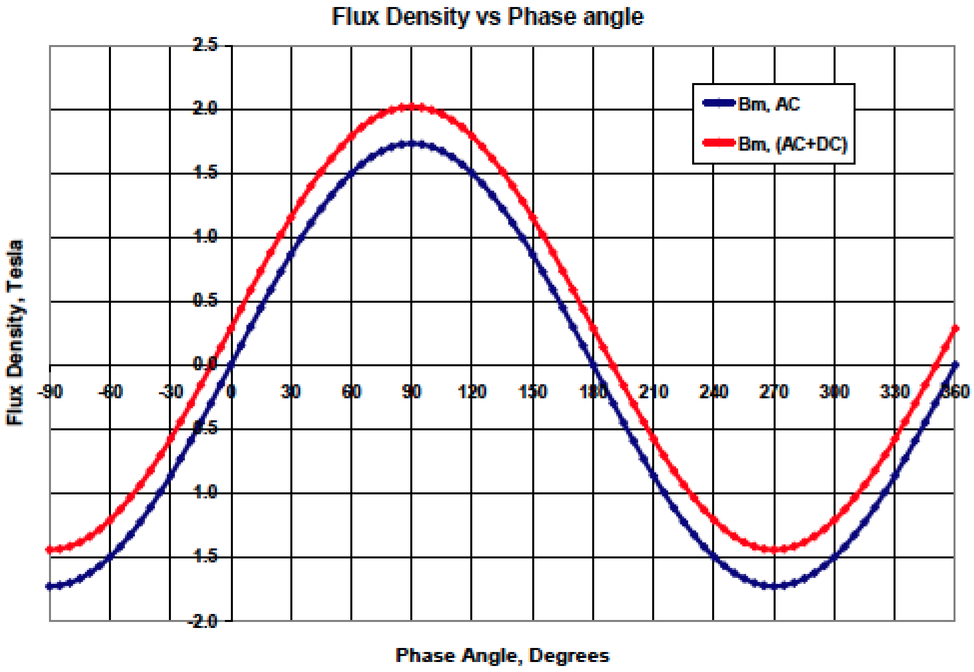

Figure3.3: flux density shift in the core caused by DC (Røen, 2016)

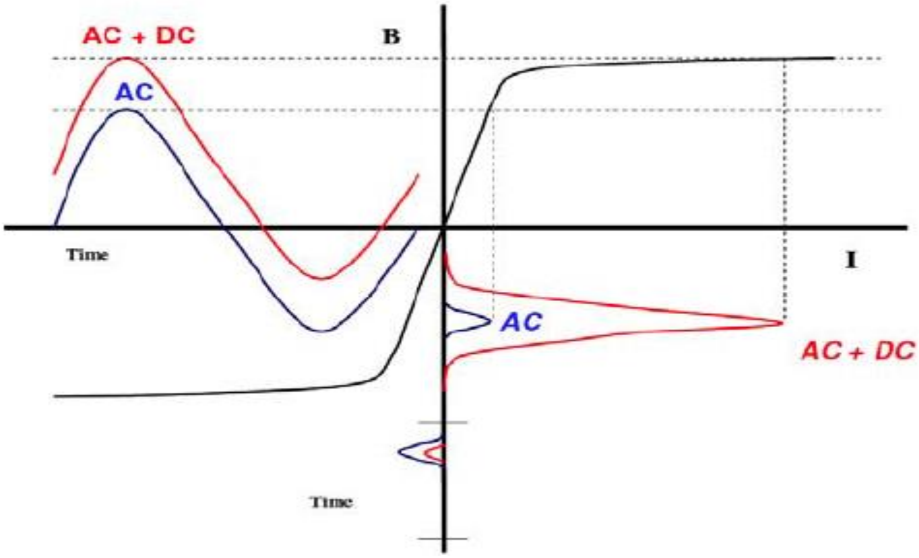

Figure3.4: Part-Cycle, Semi-Saturation of Transformer core (Røen, 2016).

3.4.5 Harmonics Generation

A distorted waveform creates harmonic currents, which in turn generates heat. Albertson et al. (1973) established that localized heating can occur shortly after exposure to a GIC, and the effects may be cumulative. Overheating can shorten the life of a transformer, and if severe enough, it could result in an early catastrophic failure.

In addition, harmonics can resonate with inductances and capacitances in the power system and can create voltages that are much higher than nominal, which also can lead to transformer failure. Harmonics also might cause erratic behavior in voltage regulators and relays, resulting in system voltage decreases and, consequently, adverse effects of the power transfer capability of lines. In other cases, harmonic blocking measures may be activated, thus preventing some relays from operating when they should, and the harmonics may cause trips that should not happen (Kirkham & Makarov, 2011).

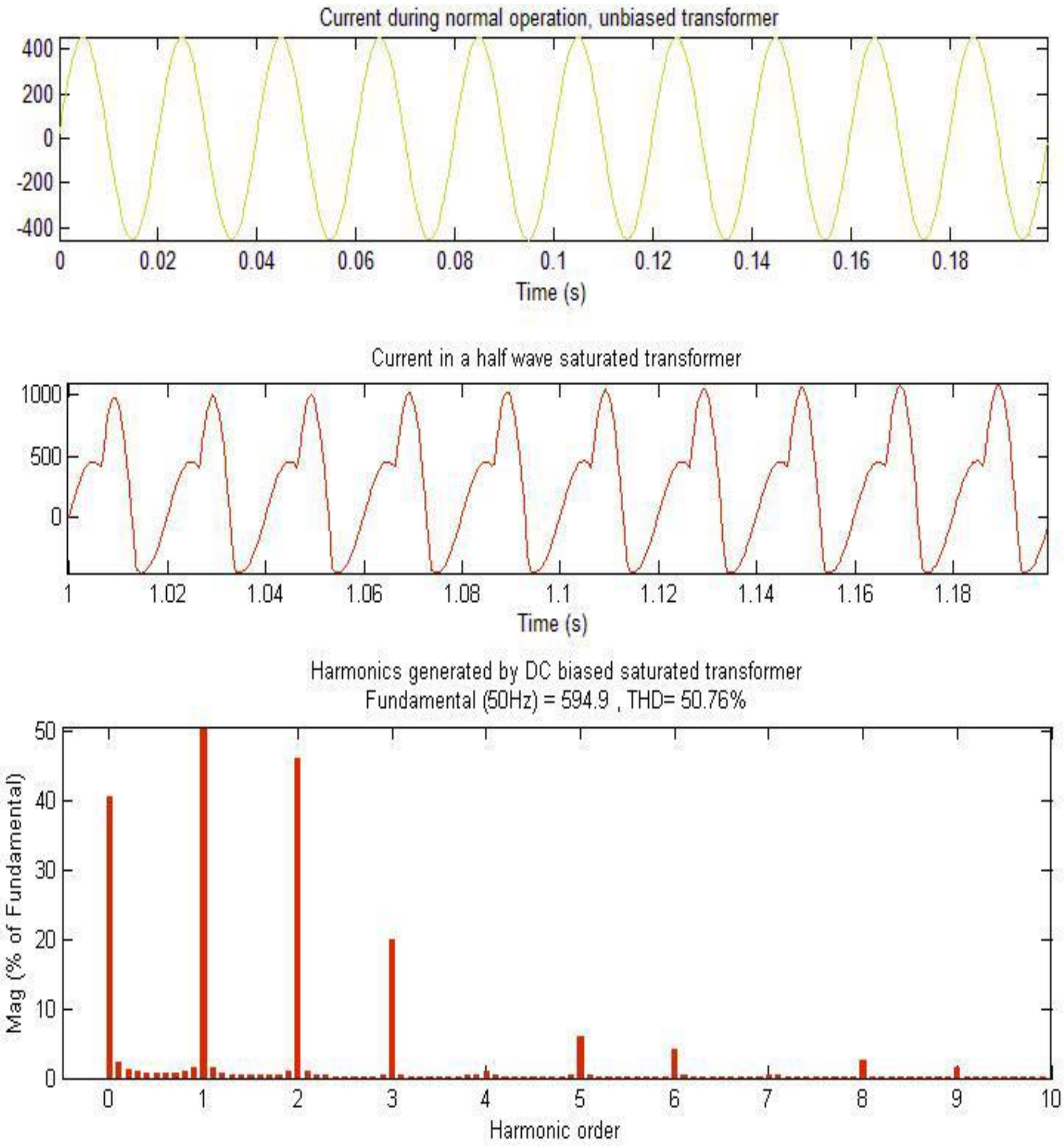

Figure3.5: Example of harmonics generation due to GIC

Top: Graph shows current waveform during normal operation. Mid: Current wave form when the same transformer, as used in the top graph, is subjected to DC-bias. Notice the strong deformation due to increased magnetization current. Bottom: Spectrum showing harmonics contents in the DC biased current shown in the mid diagram. THD, Total Harmonic Distortion is a measurement of the harmonic distortion content (Thorberg, 2012).

3.4.6 Reactive Power Consumption

Another result of increased magnetization current is a substantial increase of reactive power consumption as shown in Figure 3.6. This can lead to instability in the power system and thus the risk of voltage collapse. This has also been shown through the simulations mentioned above.

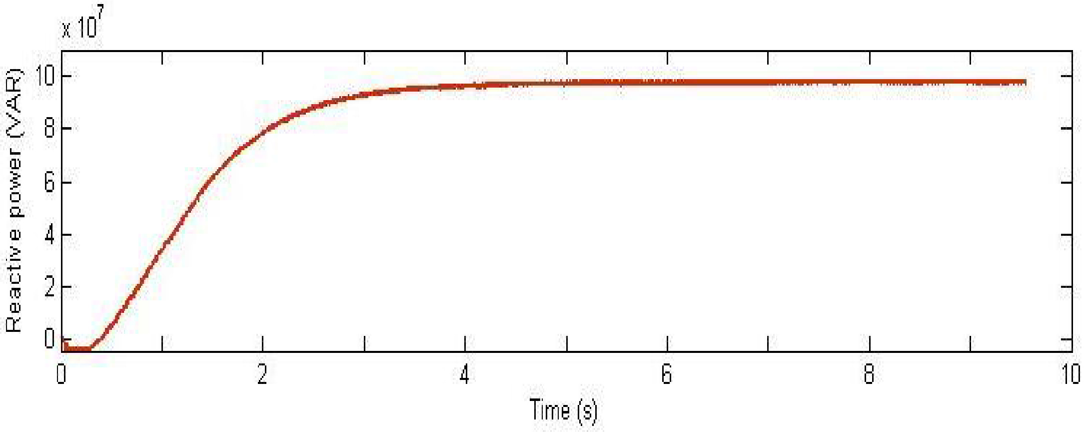

Figure 3.6: Reactive power consumption in the simulated transform. At time zero a constant GIC starts to flow through the transformer and the core starts to saturate. Once the core is saturated (about time 4s) the reactive power consumption remains constant (Thorberg, 2012).

3.5 Review of Historical Events

3.5.1 The Carrington event, September 1, 1859

The Carrington event, named after British astronomer Richard Carrington, is both the strongest and one of the earliest ever recorded geomagnetic storms.

On the morning of September1^{st},1859, Richard Carrington observed a previously unknown phenomenon, an extremely intense solar flare. The geomagnetic storm struck 17 hours later and it lasted for days. Reports of the storm came from all over the world. Auroras where observed as close to the equator as the Caribbean. By some reports, it was bright enough to read newspapers by the light of the aurora alone.

Telegraph systems went down all over Europe and North America, in some cases even giving electrical shocks to operators and causing fires (Røen, 2016).

3.5.2 The Hydro-Québec event, March 13, 1989

At 2:44 a.m. on March13^{th}, 1989 a 100 ton static VAR capacitor at Chibougamau sub-station, Québec, Canada, tripped and went offline due to GIC causing a protective relay to sense overload conditions.

The tripped VAR capacitor caused a cascade of failures throughout the Québec power grid; most notably five transmission lines from James Bay were tripped causing a loss of 9,450 MW. The total load in the grid at the time was about 21,350 MW. A mere 75 seconds after the first capacitor went down most of the province was left without power. Automatic load reduction systems tried to restore balance in the power system by disconnecting towns and regions but failed. This cascade of spreading failures was much too fast for any meaningful form of manual intervention by operators to take place. 6 million of Hydro-Québecs customers were left without power for up to 9 hours.

About 200 other separate events due to the storm were also reported from North America, of which the catastrophic failure1 of a step-up transformer at the Salem Nuclear Power Plant in New Jersey was probably the most serious one (Thorberg, 2012).

3.5.3 The Halloween Storm, October 30, 2003

Two CMEs hit Earth close to each other in time. The first erupted from the Sun at 11:10 (UTC) on the 28th of October 2003 and hit Earth about 19 hours later at roughly 06:10 (UTC). The second CME erupted at 20:49 (UTC) and reached Earth at 16:20 (UTC). At 20:04 (UTC) the storm peaked and the geoelectric field reached values of 2 V/km in the Malmö region (Thorberg, 2012).

This storm had a wide array of consequences for different technological systems. The most effects in power systems. Among other affected systems can be mentioned, the Wide Area

Augmentation System (WAAS), a navigation system based on GPS, operated by the Federal Aviation.

Administration, which was out of service for 30 hours and also the ADEOS-2 satellite that was severely damaged due to the storm (Thorberg, 2012).

3.5.3.1 Sweden

On October 30 21:07 (local time, UTC+1) 2003, a blackout2 occurred that lasted for 20-50 minutes and affected 50 000 customers in Malmö and surrounding areas. The root cause was a relay in the 130 system. The relay was set too sensitive to the third harmonics (150 Hz) of the fundamental frequency (50 Hz) which was a result of transformer saturation due to GIC caused by geoelectric field values of 2 V/km.

Also during the Halloween storm, a transformer at a Swedish nuclear power plant experienced a 13˚C increase in top oil temperature in a transformer containing 69 tons of oil before mitigating action were taken to allow the transformer to cool down (Thorberg, 2012).

3.5.3.2 South Africa

The same storm is reported to have caused significant transformer damage in South Africa. Over 15 transformers in South Africa were damaged during this period, some beyond repair (Thorberg, 2012).

3.5.4 Norway

Until today, Norway has not uncovered any serious or widespread system damage to be caused by geomagnetic disturbances (GMDs). But still, there are some incidents worth mentioning, such as the activation of a 90 MVAR shunt capacitor at Kristiansand in 1999, caused by GIC flows. Another example happened at Lyse in 2004 where a Buchholz relay tripped and led to disconnection transformer (Røen, 2016).

3.6 GIC mitigation Strategies

3.6.1 Blocking GIC Flow

The most fundamental approach, though not necessarily practical based on system considerations, is to block the path of GIC. This would involve either the elimination of one of the two neutral ground connections at either end of a transmission line, inserting series compensation on the connected transmission lines or use of a blocking capacitor in the neutral ground connection.

With any of these options, GIC cannot flow through the transformer windings, and the problems caused by semi cycle saturation namely harmonics, heating, and Voltage Ampere Reactive (VAR) consumption are eliminated. Implementation of any blocking solution should be accompanied by a system study since elimination of GICs on one transmission line may significantly change the GIC impact to other parts of the system and can influence system operations. In other words, GIC should be viewed as a network problem ((NERC), 2013).

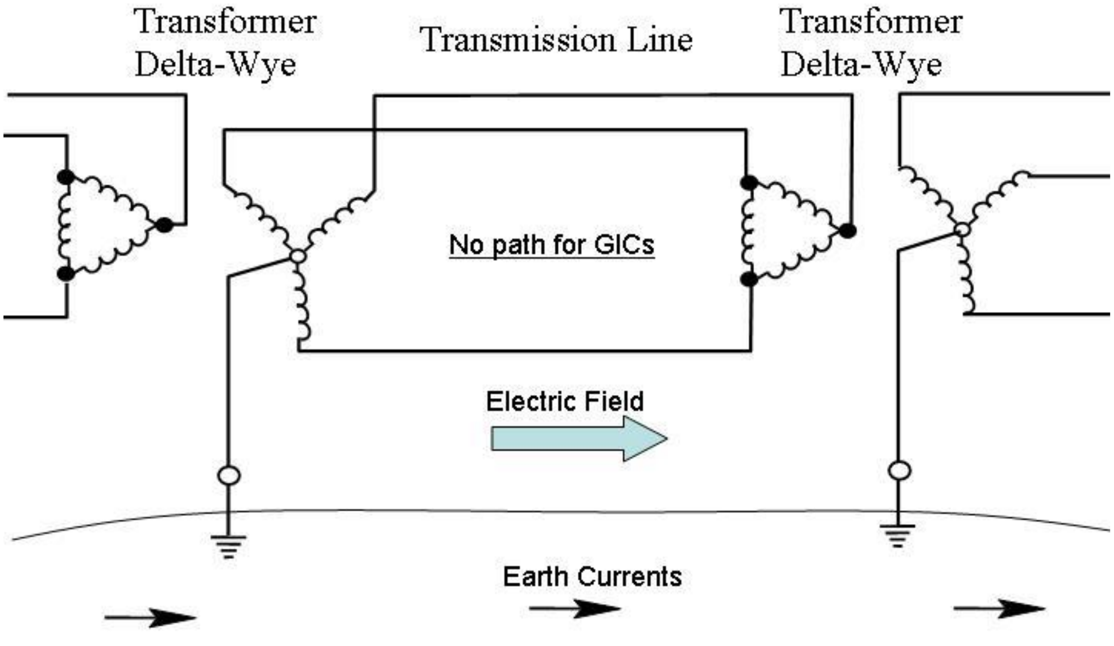

Figure 3.7: Schematic showing that GIC have no path if one end of transmission line has a delta connected Transformer ((NERC), 2013)

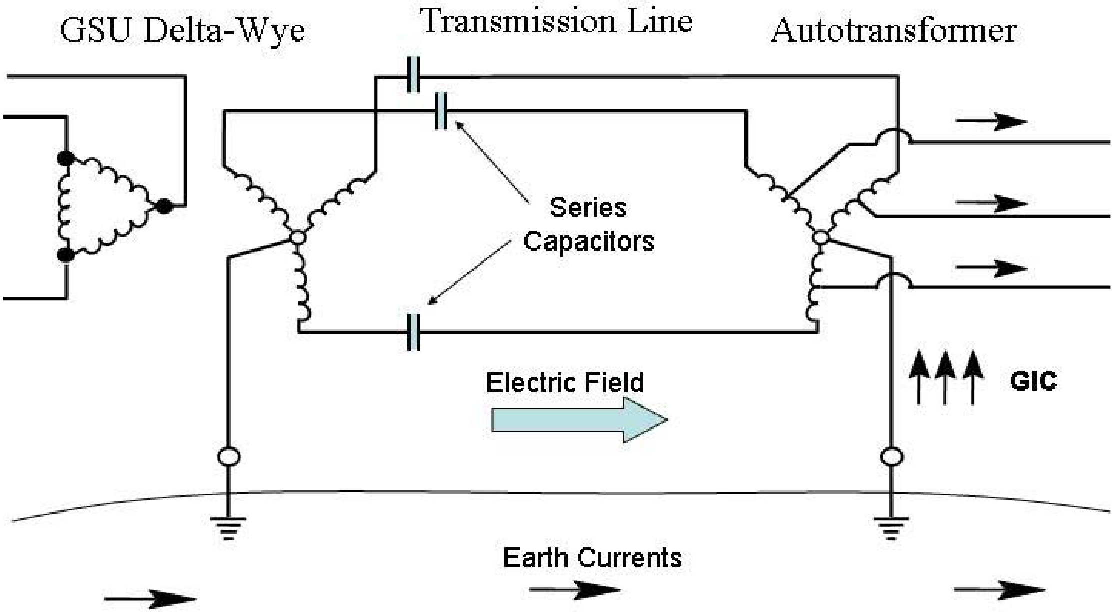

Figure 3.8: Series compensation (capacitors) interrupts the GIC path ((NERC), 2013)

3.6.2 Reducing GIC Flow

One of the additional approaches that reduce GIC is the use of a 2.5 to 7.5 ohm resistance in the ground connection (at the same location as the capacitor in Figure 3.9). This has been called a neutral grounding resistor or a neutral resistor/blocking device (NRBD), even though, strictly speaking, it does not fully block current flow. The reduction in GIC levels depends on the ground resistance, transformer winding resistances, and transmission line phase resistance for the specific situation where it is applied, but typical levels that can be achieved are 60-70 percent reduction. The issues associated with this approach are identical to all of the issues that come with resistance grounding, namely selecting a ground resistance value based on fault current and relaying requirements ((NERC), 2013).

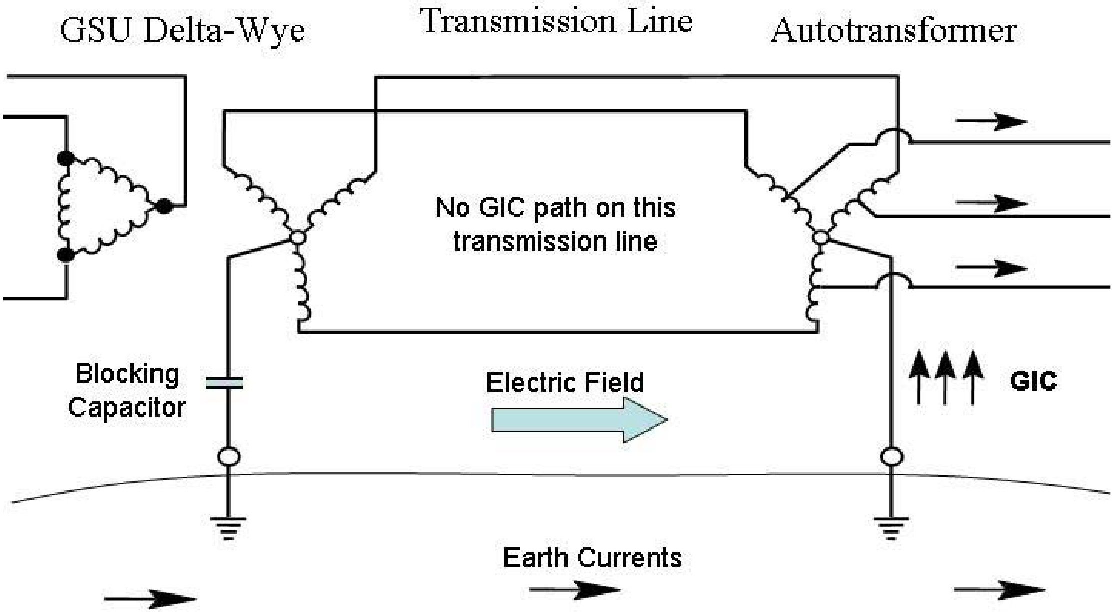

Figure 3.9: Blocking capacitor inserted in the neutral-ground connection to block GIC ((NERC), 2013).

Chapter Four

Results and Discussion

4.1 Results

In order to investigate the effects of GIC on national power grid transformers; sequential measurements (every five minute) each of winding current, voltage and winding temperature for IZBA (110-33) transformer in 27/2/2017 when a blackout of about 4-hours occurred during that day, was collected from national center of control. The measurements were plotted in figure4.1 then the corresponding Dst index observations were plotted and stacked with those measurements.

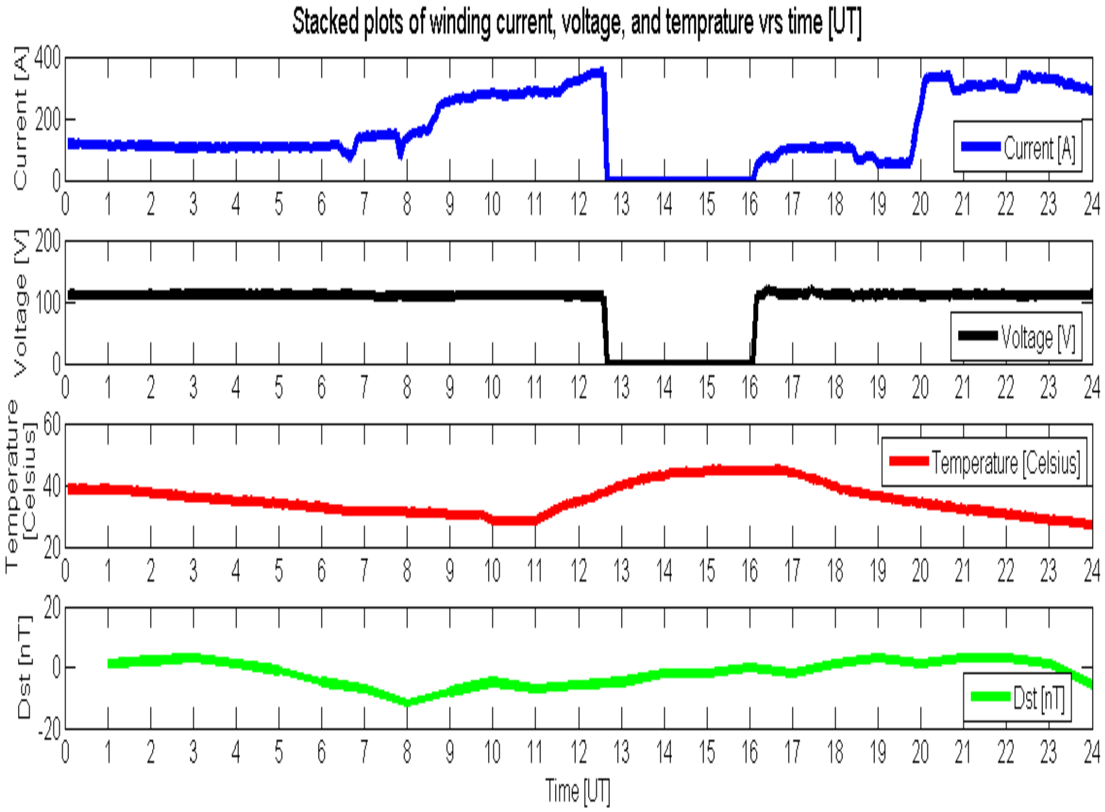

Figure 4.1: measurements of winding current, voltage, winding temperature and Dst index observations

4.3 Discussion

Investigating data showed that the winding current was increased almost five hours before blackout and vanish to zero during the time of blackout which continued for duration of almost 4-hours from 12:35:00 to 16:00:00 UT.The current also increased gradually after the blackout termination. While the voltage was stayed almost steady 5- hours before blackout event and continued almost steady after blackout. Moreover, the winding temperature was increased almost 2- hours before blackout and continued to increase to some peak occurred mean while the period of blackout and decreased on more time. The Dst index observations showed a corresponding minor storm with Dst> -50 during occurrence of blackout which was showed to appear on the recovery phase of that storm. These storm maybe it was induce a GIC in this transform leads to a higher magnetizing current, causes a significant increase of eddy and circulating current losses in both windings of the transformer, causing heat generation and power losses. These results interpret the possible contribution of space weather effects on the stability of the national power grid.

Chapter Five

Conclusion and Recommendation

5.1Conclusion

Geomagnetically induced current GIC is a consequence of the strong disturbances in the earth magnetic field due to the activity of the sun. The significant influence of GIC in the ground-based technology systems is its impact on power grid systems.The transformer in the grid has been shown traces of influence of GIC which is someThing very important to be considered even in low latitude power grid systems.

There are several strategies to mitigate the impact of GIC such as (Blocking GIC Flow, Reducing GIC Flow), both could be followed to prevent power grid from blackout events related to geomagnetic disturbances. From these results, we conclude that there is a probability of associating between the geomagnetic storms and blackouts.

5.2 Recommendation

The results was obtained from one transformer in the grid; therefore we recommend that to use more data from different transformers in the grid during the occurrence of the geomagnetic storms, also we recommend the National Electricity Authority in Sudan to consider the space weather as one of the reasons for blackouts beside the other technical reasons , also customize unit for GIC monitoring and research, we also recommend the institute of space Research and Aerospace to publish daily space weather report to take all possible precautions to avoid the damage of transformers.

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Bibliography

(NASA/ESA), S., 2000. *Earthsky.* [Online]
Available at: http://earthsky.org/space/what-are-coronal-mass-ejections
[Accessed 4 february 2018].

(NERC), T. N. A. E. R. C., 2013. *Geomagnetic Disturbance Planning Guide.* Atlanta, s.n.

Abd-Allah, A. M., 2011. *Ionospheric disturbance during,* Helwan: The University of Helwan.

Anon., 2017. *Solar Cycle Science.* [Online]
Available at: http://solarcyclescience.com/forecasts.html
[Accessed 4 february 2018].

Barbosa1, C., Alves, L., Caraballo, R. & Hartmann, G. A., 2015. Analysis of geomagnetically induced currents at a low-latituderegion over the solar cycles 23 and 24: comparison between measurements and calculations. *j.space weather clim,* pp. 1-9.

Center, N. S. W. P., 2012. *A Profile of Space Weather,* Boulder: National Oceanic and Atmospheric Administration (NOAA).

Commerce, U. D. o., 2011. *Storms from the sun,* s.l.: National Oceanic andAtmospheric Administration (NOAA).

GIRGIS, R., VEDANTE, K. & GRAMM, K., 2012. *Effects of Geomagnetically Induced Currents on Power Transformers and power systems.* Paris, International council on large electric systems, pp. 1-8.

Group, H. R. a. T. S., 2005. *Transformers: Basics, Maintenance, andDiagnostics.* Colorado: s.n.

Gurevich, V., 2011. Protection of Power Transformers Against Geomagnetically Induced Currents. *SERBIAN JOURNAL OF ELECTRICAL ENGINEERING,* 8(2), pp. 333-339.

Hanslmeier, A., 2007. *The sun and space weather.* 2 ed. Netherlands: Springer.

HUTCHINS., T., 2012. *GEOMAGNETICALLY INDUCED CURRENTS AND THEIR EFFECT ON POWER SYSTEMS,* Urbana, Illinois: University of Illinois at Urbana-Champaign.

Kirkham, H. & Makarov, Y., 2011. *Geomagnetic Storms and LongTerm Impacts on Power Systems,* s.l.: s.n.

Moldwin, M., 2008. *An Introduction to space weather.* New York: Cambridge University Press.

NASA/SDO, 2014. *space weather.* [Online]
Available at: https://www.nasa.gov/content/goddard/sun-release-x20-class-flare-on-oct-27-2014
[Accessed 4 february 2018].

NASA, 2017. *Energizing Space.* [Online]
Available at: https://ase.tufts.edu/cosmos/print_images.asp?id=29
[Accessed 4 february 2018].

NOAA, 2011. *SPACE WEATHER PREDICTION CENTER.* [Online]
Available at: http://www.swpc.noaa.gov/noaa-scales-explanation
[Accessed 4 february 2018].

onen, R. H., 2013. *Geomagnetic activity and its sources during modern solar maximum,* s.l.: University of Helsinki.

Røen, B., 2016. *Geomagnetic Induced Current Effects onPower Transformers,* s.l.: Norwegian University of Science and Technology.

Sciences, S. (. &. E. a. t. R. S. A. o., 1995. *windows to the univers.* [Online]
Available at: https://www.windows2universe.org
[Accessed 4 february 2018].

StenOdenwald, D., 2012. *Mathematical problems featuring space weather applications.* s.l.: National Aeronautics and Space Administration.

Thorberg, R., 2012. *Risk analysis of geomagnetically induced currents in power systems,* s.l.: Lund University.

Trivedi, N. B., Vitorello,´ ., Kabata, W. & Dutra, S. L. G., 2007. Geomagnetically induced currents in an electric power transmission system at low latitudes in Brazil:A case study. *Space Weather,* pp. 1-10.