Geomagnetic storms and their impacts on Ethiopian power grid

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In present work we analysed eight geomagnetic storm events in 2015/2016 and studied the possible influence of these events on Ethiopian power grids. The results showed that the majority of the forced power outages occurred in the period of the main phase of events and the recovery period of the geomagnetic storms. The geomagnetic storms are characterised by different indices and parameters such as the disturbance storm time (Dst) values, coronal mass ejection (CME) speed, solar wind speed (V_{sw}) and interplanetary magnetic field (IMF-Bz) on the selected dates. In most cases the observed geomagnetic storms were produced by the CME-driven storms as they show a storm sudden commencement (SSCs) before the main storms, and also have the short recovery periods. The sudden jumps of the solar wind velocities and IMF-Bz are also consistent with occurrence of the CMEs. Moreover, this effect can be traced in changes of Earth magnetic field during geomagnetic storm and quiet days. The observed CME-driven storms can produce highly variable magnetic fields on the transformers and provide forced outages, however the studied outages have not been recognised as those one driven by a geomagnetic storm.

Key words: GIC, Geomagnetic storm, Solar variability, equatorial ionosphere

INTRODUCTION

The Sun as a dynamic object releases constantly energetic solar materials, which affects the magnetosphere and ionosphere of the Earth [5–7]. Moreover, this sudden release of energy and particles is available to harm the technologies on the Earth [1–4].

The interaction of the Sun ejecta and the Earth magnetic field at the magneto-pause causes the so-called geomagnetic storm. Solar storms are the sudden eruptions of magnetised gas in the Sun outer atmosphere or corona, which are caused by the variability of photospheric magnetic fields commonly associated with the flashes of electromagnetic radiation, solar flares ranging from X-rays to visible wavelengths, accompanied by the eruption of a giant cloud of magnetised plasma, a coronal mass ejection (CME). Fast CMEs drive the shock waves which can accelerate particles to energies of several GeV, which is called solar energetic particle events. Such powerful solar storms can disrupt communication and navigational equipment, damage satellites and even cause blackouts by damaging the power plants and electrical grid components [8, 9, 14, 15].

The damage of power grids can be inflicted be-

cause of the high levels of stray magnetic flux and circulating currents that were occurring outside the transformer core due to the half-cycle saturation. The level of damage strongly depends on the strength of the storm. The concentration of the storm fluxes near the transformer can exceed the normal working exposures for its components and lead to almost immediate and severe hot-spot heating insults inside the transformer and its structural components [16–18]. Furthermore, one minor exposure may not be sufficient to cause the insulation failure, but it can be accumulated over several insults up to the failure point.

Solar storm has three major components: solar flares, solar proton events (SPEs) and CMEs. When the interplanetary shocks associated to CME hit the Earth, they generate the intense magnetosphere and ionosphere current, which generates the induced current on the ground known as the geomagnetically induced currents (GICs). In fact, GIC is the most common phenomena in the high latitude region due to the effect of intense and frequent space weather perturbation. However, several studies([11, 20, 21] and references therein) showed that large geomagnetic disturbances during the major space weather storms

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may also occur at much lower latitudes. In addition, Kappenman [22] found that large GICs have also been associated with the impulsive geomagnetic field disturbances as during the sudden storm commencement (SSC), which occurs due to the sudden increase in the solar wind dynamic pressure. Hence, in such conditions large GICs can be observed even at low latitudes. Moreover, there is a confirmation that the geomagnetic field disturbances associated with the ring current intensification may be an additional source of the large magnitude and long duration GIC in power grids in the low latitude regions [10]. At the same time, the high speed CMEs and fast solar winds are able to compress magnetic fields of the Earth and hence, the magnetosphere and ionosphere currents caused by SSC and sudden impulse (SI) events can pose the GIC risk in lower to equatorial region [25, 26, 28]. According to all studies discussed above, it is important to take into account GIC issues not only at high latitude, but also in low-latitude up to equatorial networks. For instance, a couple of similar researches have already been done in the mid-low latitude regions such as China [28].

Huttunen et al. [19] showed that the largest GIC amplitudes are driven by the interplanetary coronal mass ejections (ICMEs), while lower amplitudes are usually generated by co-rotating interaction regions. From a GIC perspective, the rate of change B or dB/dt is the most important attribute of the impulsive geomagnetic field disturbance environment. Based on the results of earlier works like [21], this local dB/dt level is higher at the equatorial region than at the high latitude during the SI event. This is opposite to the severe storm event observed on November 20, 2003, where the dB/dt level was recorded higher at the high latitude region.

Power system impacts from the geomagnetic storms were firstly observed in 1940 and its importance grew with the development of the power system in recent years. The generation of a geomagnetic storm happens when the Earth magnetic field captures ionised particles carried by the solar wind through to the coronal mass ejections or coronal holes at the Sun. Usually the disturbances observed at the Earth surface can be characterised as very slowly varying magnetic fields with fast with fast increasing in a few seconds and pulse widths of up to one hour. The rate of magnetic field change plays a key role in the changing of the electric field of the Earth and therefore, it may induce additional DC-current flow in the power transmission network. In this way, the power systems vulnerability and its possible damages can be explored through the study of the geomagnetic storm phenomena, which is closely associated with the well-known cycle of Solar magnetic activity and the observed variation in the number of sunspots on the solar surface [24, 27].

The changes in the magnetic field in the vicinity of conductors (e.g. wires, transformers etc) are

able to induce the voltage, and thereby the current, which is directly proportional to the voltage. Such induced voltage-current system can cause problems on the transformers leading to complete collapse or blackouts in some grid systems. Moreover, electric lines (the length of which extends for several kilometers) can be damaged by this effect. The quasi-direct currents in these lines induced by the geomagnetic storms are harmful to the electrical transmission equipment, particularly for generators and transformers since they induce the core saturation constraining their performance (as well as tripping various safety devices) and cause heating of coils and cores. Such heat can not only disable or destroy them, but also induce a chain reaction that can blow transformers throughout the system. The susceptibility of electrical power grid to disruption and damage from the solar storms depends on many factors like the latitude, strength of the geomagnetic storm, Earth ground conductivity, orientation of the power line, length of the transmission line, power grid construction etc.

Continuous and reliable supply of the electricity is an essential element necessary for the existence and development of all countries since the electric power sustains water supplies, goods production and food distribution, fuel and communications industries etc. Although Ethiopia produces a significant amount of electric power from the hydroelectric generators, wind turbines and the solar panels, but power outages still remain serious problem for the Ethiopian power authority. For instance, now Ethiopia is suffering from series of the continuous power disruption everyday. The primary consequence of severe geomagnetic storm would be the disruption of reliable electricity service to large part of Ethiopia through the widespread damage of high voltage transformers and other critical components of the Ethiopian Power Grids (e.g. Gibe I, Gibe II, Tekeze and Tanabeles grids) and new emerging power grids like the Renaissance dam, which should generate 6 GW of power. Since the functioning of society and economy depend largely on the availability of electricity, different companies, households, schools, industries, any private and government sectors are affected by the power interruption and therefore unable to perform their day to day activities. The situation is even more complex for the industrial sector due to the fact that the shortage of power are unable to produce necessary demand of high-quality industrial goods leading to the shortage of products in the stock.

Currently the level of electric power produced in Ethiopia is fair enough to unsure the society, however there is continuous interruption of power, which reasons are not identified well. Since Ethiopia is located near the equator and belongs to the low latitude countries, the geomagnetic storm intensity is relatively small here. However, the power grid GIC is not related only to the intensity of geomagnetic

storm, but also the Earth electrical structure and the actual power grid parameters are able to affect the magnitude of GIC [12].

In present work we tried to identify the possible effect of the space weather on the forced outages of the power systems in the country. For this purpose, we analysed the correlation between the frequency of power outage occurrence and the geomagnetic storm intensity, which are inferred from the values of disturbed storm index.

DATA AND METHODOLOGY

We analysed eight geomagnetic storm events observed during 2015-2016 and their effect on the power outage in the Ethiopian power grid. The data on solar wind parameters such as the solar wind speed (V_{sw}), the Dst index and the interplanetary magnetic field IMF-Bz are obtained from the world data center¹. The frequency of the forced outages is calculated from the Data of Ethiopian power Authority. Geographical wiring diagram of the dual voltage Ethiopia power grid is presented in Fig. 1.

Fig. 1: Geographical wiring diagram of the dual voltage Ethiopia power grid. Adopted from [12].

During the period of the study there were many outages, however the part of them were scheduled for maintenance and forced outages by the Ethiopian power authority workers. These scheduled outages have been done because of the grids overheating, excitation phase over the voltage speed sensor, low frequency, load shading due to the generator problem or the transformer replacement due to its aging. All these outages are summarised in Table 1.

The outages discussed above occur in the rainy

season of Ethiopia, when $> 90\%$ of the power source is produced by the hydroelectric stations. It is important to notice that there is a power interruption due to the shortage of water in dams, however we did not consider these seasons in our study. Except for the storms in March 2015 and 2016, all cases were not exposed to such interruption due to the shortage of water in our dams. Thus, we believe that our study is not affected by the meteorological effects, mechanical failures of electrical appliances due to aging and factory defects. In our analysis we consider only outages caused without human impact.

We analysed the effect of geomagnetic storm on the occurrence of power outage in the Ethiopian power grid during the main and recovery phases of the selected geomagnetic storms. Qualitative correlation analysis was made for the solar/geomagnetic indices and the number of forced power outages.

RESULTS AND DISCUSSION

The interaction of CMEs with the Earth magnetic field generates the series of processes in the magnetosphere that lead to the disturbances seen in the ionosphere and the geomagnetic field. The details of the ionospheric and ground magnetic field disturbances are considered. To describe the magnetospheric response to the CMEs it were used the ionospheric and magnetic field observations in combination with the data on forced outages collected by the Ethiopian Electric power Authority offices.

The observed changes of geomagnetic field during a geomagnetic storm are essential consequences of strong and rapid magnetospheric processes, changes under the solar wind actions and CMEs. In this paper, we used the classification of the geomagnetic storms used by [23, 27] and references therein, according to which the geomagnetic storm can be classified based on Dst index levels as a weak ($-50 \text{ nT} \leq Dst < -30 \text{ nT}$), moderate ($-100 \text{ nT} < Dst < -50 \text{ nT}$) or intense ($Dst < -100 \text{ nT}$).

The average speed of CME on March 15, 2015 and the corresponding solar and geomagnetic conditions are presented in Fig. 2. The coronal mass ejection (CME) released from the Sun as observed by SOHO on March 15, 2015 was analysed in relation to the effect on Ethiopian power grids. The CME reached the magneto-pause on March 17, 2015 and its impact was analysed. As the SOHO observations show, the CME was heading towards the Earth with the speed of 718.5 km/s from the corona on March 15, 2015 and reached the Earth magnetosphere in 2.4 days (~ 58 hours) causing a sudden increase in the Dst index called SSC to 50 nT followed by a continuous decrease of Dst index down to -220 nT on March 18, 2015. The main phase of the storm lasted for many hours.

¹<http://wdc.kugi.kyoto-u.ac.jp/index.html>

Table 1: Monthly outage reports from Ethiopian electric power Authority between January 2015 and March 2016

Month and Year	Outages			
	Storm Forced	Other factor	Planned	Total
January 2015	0	105	4	109
February 2015	0	80	7	87
March 2015	43	59	4	143
April 2015	0	94	28	122
May 2015	0	75	0	75
June 2015	20	69	12	101
July 2015	0	118	6	124
August 2015	66	8	9	83
September 2015	21	95	16	132
October 2015	4	5	4	13
November 2015	0	208	13	221
December 2015	93	96	11	200
January 2016	0	117	9	126
February 2016	0	182	15	197
March 2016	70	190	26	286

The result showed that the storm was intense. The additional analysis of the solar wind and the interplanetary magnetic field in the magnetosphere found that the solar wind speed on March 16, 2015 has suddenly increased from zero to about 600 km/s on March 17, 2015 and has been maintained for several days. Since the geomagnetic storm can reach the Earth at any time (from 18 hours to 4 days) after leaving the Sun, and its duration is typically 1-2 days, it can be concluded that the forced outage was the result of inductive voltage on the grids. The result also reveals that the recovery from severe space weather events could take considerable time. After the observed event, on March 17, 2015 (see the right panel of Figure 2) the forced outages have occurred five times. Later, on March 18, 2015, 13 forced outages have occurred, and this trend was continued reaching the maximum number of forced outages (more than 20 times per day) on the recovery day March 20, 2015.

The official explanation given by the power authority was that forced outages were due to the possible overheating, vibration, high temperature of the thrust bearing, water supply, governor channel failure etc. Although the current reasons are acceptable, we cannot ignore the possibility from space weather events. According to our suggestion, the geomagnetic storm is significantly contributed to the overheating effect on the power grids by the variability of the flux in the transformer coils. In this way, the observed forced outages after the occurrence of the storm are not randomly events, but rather generated by the prolonged effect of the storm in the form of in-

ductive currents. Since the IMF-Bz is southward on days 17-18 it implies the possibility of reconnection of the IMF-Bz with the Earth magnetic field affecting the low and mid latitudes of the ionosphere.

Figure 3 shows the storm condition and their effect on power grid during June 23, 2015. The geomagnetic storm event was observed on June 22 and lasted for a long recovery period impacting the power grids. The geomagnetic storm was classified as an intense storm. As the *Dst* index reveals, the storm sudden commencement occurred on day June 21, 2015 and the main phase was on June 23, 2015. The recovery phase lasted up to June 28, 2015. During the storm period, the forced outages had been observed every day starting from the main phase until the *Dst* value attained its normal value. However, during the recovery period 19 outages were observed. The source of geomagnetic storm was the fast CME coming with the speed of 1366.1 km/s, the time needed to arrive to the magnetosphere was around 1.27 day and its impact was directly observed at the time of arrival. The solar wind speed jumped from 0 to 800 km/s on June 23, 2015 and maintained this speed until June 27, 2015. IMF-Bz also showed the rapid fluctuation by changing its polarity from zero to -20 nT, then tried to recover again continuously two days from North to South showing the occurrence of geomagnetic storm.

The height profile of CME, solar/geomagnetic conditions and their effect on power grid during the August 27, 2015 storm are shown in Fig. 4. The geomagnetic storm came from the CME event that occurred on August 25, 2015 and had the speed of

304.5 km/s. This CME has reached the Earth after 5.7 days and produced a moderate geomagnetic storm. The other disturbance of the *Dst* index observed on August 27, 2015 was from the other storm that had happened before this day. The features of the solar flare that erupted on September 18, 2015 at 04.35 UT explained and provided an illustration of the impacts associated with the flare. In addition, it were observed the sub-storms in magnetosphere triggered by the CME shock. The CME radio bursts had a speed 823 km/s at the corona and reached the magnetosphere on September 20, 2015. The magnetic field SSC signature was observed at 02.30 UT on September 18, 2015 marking the shock within the magnetosphere due to the arrival of the CME shock front at the magnetopause. Over the next few hours the *Dst* value reached its main phase leading to repeated cycles of the current buildup in the power grids.

Figure 5 shows the geomagnetic storm on September 18, 2015, which coincides with the SSC indicating the arrival of the CME. The rapid magnetic field variations associated with the sub-storms were accompanied by the power system disturbances. This result is in agreement with the results of [22]. During the main storm the *Dst* value was -80 nT (the moderate storm). IMF-Bz fluctuated between 10 and -10 nT. The observed solar wind increased from 400 km/s to 560 km/s. The total power outages of this event starting from the SSC to the recorded recovery phase occurred 40 times. The continuous fluctuations led to the continued outages in power grid. The interplanetary magnetic field was continuously changing its direction.

In Figure 6 presents the similar properties for the storm on October 7, 2015. Another CME event happened on October 5, 2015. The CME at the corona had the speed 713.8 km/s and reach the Earth after 2.43 days. In addition, Figure shows a jump of the solar wind speed at the magnetosphere from 0 km/s to around 800 km/s, while IMF-Bz fluctuates between the amplitudes of 10 and -10 nT. This results to the intense geomagnetic storm with *Dst* value of -120 nT on December 8, 2015. The observed outage for this storm was on December 10, during the recovery phase. Moreover, IMF-Bz was highly fluctuating for more than 4 days causing repeated forced outages.

The similar data for events on December 20, 2015 is shown in Figure 7. Lindsay et al. [24] and many other studies have indicated that the geomagnetic storms were accompanied by the high solar wind velocities, enhanced solar wind dynamic pressure and CME. The CME ejected on December 18, 2015 at the corona had the CME speed of 465.4 km/s and the arrival time at the magnetosphere was calculated to be around 3.7 days. This CME was responsible for the formation of enhancement of the solar wind speed at the magnetosphere; it increased

to 500 km/s on December 20, 2015 and recovered on the next day at 400 km/s. IMF-Bz was southward on December 20, 2015 and recovered on day December 21, 2015. The *Dst* index showed the intense geomagnetic storm on December 20, 2015. The *Dst* index showed the long recovery period from December 21-24, 2015. The storm caused the forced voltage outages on the Ethiopian power grids. As we see in Figure 7 the high frequencies were registered during 3 days (December 22-24) with 42 forced outages in total indicating that the forced outages in power grids are more prominent during the recovery periods. The changes in *Dst* in both cases are able to cause another type of risk for power systems, because the flare observed on December 29, 2015 was a source of the CME, which produced a magnetic storm on January 1, 2016. This storm recovered fully to its normal value on January 6, 2016. During the main storm the interaction of the first CME with the magnetosphere caused the decrease in the *Dst* value by 100 nT within 3 hrs. Thus, the occurrence of the triggered substorm caused the the rapid change in the magnetic field inducing considerable GIC in the power system. The magnetic field variation for this event was large and produced 52 outages until its recovery period. During the main storm and recovery periods the solar wind speed increased from 400 km/s to 600 km/s, while the IMF-Bz fluctuated between 10 nT northward and 10 nT southwards (see Fig. 8).

The solar and geomagnetic conditions and their effect on power grid during the March, 6 2016 storm are illustrated in Fig. 9. The geomagnetic storm was a moderate one, the frequency of outage observed during the storm events was maximum during the storm sudden commencement time. A total of 36 forced outages occurred on March 6, 2016. 12 forced outages were happened during the main phase and 23 were during its recovery phase. The official explanation given by the Ethiopian power Authority were overheating, vibration, over-voltage on the grids resulting the current overflow. This geomagnetic storm was different from the other storm since the CME happened with the component speed of 257.7 km/s at the position angle of 720 from the Sun-Earth line on March 4, 2016, the front CME speed was close to 711 km/s, while the solar wind speed increased from 300 to 600 km/s on March 7, 2016. Figure 10 shows the presence of the positive correlation between the number of outages and the convective electric field of the solar wind, which can indicate the possibility of the convective electric field to be a reason of the observed forced outages.

CONCLUSIONS

Eight geomagnetic storms showed to be the result of CME, which are linked to the solar flares starting at different times in 2015/16. The observed CME-driven storms produced a number of outages due to

destabilisation and numerous component damages of the electric grids caused by GICs. We observed that the intensity of CME has a direct relation to the convective electric fields of the solar wind.

The generation of the geomagnetic storm by fast CME does not depend on the magnetic field orientation, however we noticed that CMEs with southward IMF-Bz tend to affect electric grids more.

The obtained results show that a geomagnetic storm always occurs coherently with a continuous forced outage. Moreover, the majority of the forced outage was observed during the main phase and the recovery period of the geomagnetic storm indicating the possible impact of the storm on power grids. This impact on the transmission lines are usually observed as a set of different effects like the overloading or on-line generator tripping, the increase or decrease of the system frequency, the power system voltage collapse, the generator losing synchronism, the growth of low-frequency oscillation for the large power systems and permanent damage on the transformers.

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Fig. 2: Height profile of CME on 15 March 2015 (left) and solar/geomagnetic conditions during March 2015 (right).

Fig. 3: Height profile of CME on 21 June 2015 (left) and solar/geomagnetic conditions during June 2015 (right).

Fig. 4: Height profile of CME on 25 August 2015 (left) and solar/geomagnetic conditions during August 2015 (right).

Fig. 5: Height profile of CME on 18 September 2015 (left) and solar/geomagnetic conditions during September 2015 (right).

Fig. 6: Height profile of CME on 05 October 2015 (left) and solar/geomagnetic conditions during October 2015 (right).

Fig. 7: Height profile of CME on 18 December 2015 (left) and solar/geomagnetic conditions during December 2015 (right).

Fig. 8: Height profile of CME on 29 December 2015 (left) and solar/geomagnetic conditions during December 2015 (right).

Fig. 9: Height profile of CME on 04 March 2016 (left) and solar/geomagnetic conditions during March 2016 (right).

Fig. 10: Correlation between the number of outages and the solar wind convective electric field.