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Analysis of Transformer Reactive Power Fluctuations during Adverse Space Weather

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***Abstract*—**A ground-end manifestation of space weather phenomena is known as geomagnetically induced currents (GICs). GICs flow along the electric power transmission cables connecting the transformers and between the grounding points of power transformers during significant geomagnetic storms. Zimbabwe has no study that notes if grid failures have been caused by GICs. Research and monitoring are needed to investigate this possible relationship purpose of this paper is to characterize GICs with a power grid network. This paper analyses data collected, which are geomagnetic data, which include the Kp index, Disturbance storm time (DST) index, and the G-Scale from geomagnetic storms and also analyses power grid data, which includes reactive power, relay tripping, and alarms from high voltage substations and then correlates the data. This research analysis was first theoretically analyzed by studying geomagnetic parameters and then experimented upon. To correlate, MATLAB was used as the basic software to analyze the data. Latitudes of the substations were also brought into scrutiny to note if they were an impact due to the location as low latitudes areas like most parts of Zimbabwe, there are less severe geomagnetic variations. Based on theoretical and graphical analysis, it has been proven that there is a slight relationship between power system failures and GICs. Further analyses can be done by implementing measuring instruments to measure any currents in the grounding of high-voltage transformers when geomagnetic storms occur. Mitigation measures can then be developed to minimize the susceptibility of the power network to GICs.

***Keywords*—**Adverse space weather, DST index, geomagnetically induced currents, Kp index, reactive power.

I. Introduction

GEOMAGNETIC storms are disturbances in the Earth's Magnetosphere that results from the interactions of highly energetic charged particles that outburst from the sun atmosphere. These outbursts are known as Coronary Mass Ejections (CMEs). A strong magnetic field and accompanying plasma mass are ejected into the heliosphere from the Sun's corona during a CME [1], [2]. Geomagnetic storms are registered as a disturbance in the Earth's magnetic field. Disturbances in the Earth's magnetic field can be observed as rapid increase and decrease in the earth magnetic field, thus, inducing quasi-DC electric currents as in accordance with the Faraday's law.

Grounded technological systems are likely to conduct the induced quasi-DC current. These currents are known as GICs. A lot of studies have discussed their effects in grounded technologies such as gas pipeline, railway lines and the electric grid. While high latitude regions are deemed to be highly prone to effects of GIC occurrences, several studies in mid-latitude and low-latitude have confirmed and discussed the effects of GIC in their power grids [3]-[7]. For the power grids, it is highlighted that the grounded neutral to ground terminal is the main path of the GIC.

In Southern Africa, countries such as South Africa and Namibia have done several studies on the impacts of GIC in the power grid. Several models and quantification have been tested using existing data [5], [8], [9]. Zimbabwe has power grid connections that are linked to its neighboring countries such as South Africa, Mozambique, Namibia, Zambia and Botswana. This is the first study on the Zimbabwean power grid to monitor systems in place to track the impact of adverse space weather on the Zimbabwean power grid. This paper discusses the attempts to assess the response of the Zimbabwean power grid to adverse space through monitoring the reactive power perturbations on high voltage transformers. The reactive power is one of the parameters that is highly affected by the presence of GIC in the network and thus this study opted to start with analysis of the reactive power response.

II. Reactive Power Fluctuations during Adverse Space Weather

In electrical systems, proper operation of the power system is very important. If the system is compromised, damages such due to overheating maybe experienced thus reducing the lifespan of the equipment as well as disrupting supply [10], [11]. The reactive power is one important aspect in the power system. The decrease and increase of the reactive power affect the voltage of the power transformer. In cases where the system is supporting a high load than its specification, there might be a voltage collapse [12], [13]

GIC flowing through the high voltage winding has many impacts on power transformers, including half-cycle saturation. Half-cycle transformer saturation may lead to transformer heating and reactive power losses. Fig. 1 shows the various aspects that are influenced by the flow of GICs in a transformer. Several studies have shown that reactive power fluctuates more during adverse space weather conditions [14]-[17]. These fluctuations have a potential of exposing the transformer to stresses that can compromise the operation.

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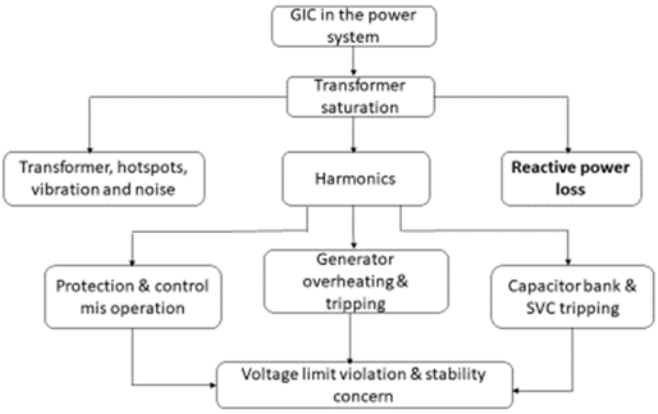

Fig. 1 GIC flowchart

If the geomagnetic disturbance is strong enough, the system may fail to handle the required reactive power because the GIC will be too large [4], [18], [19].

Assessment of the Reactive Power Behavior in the Zimbabwean Grid

This study looks at the first assessment of Zimbabwean grid regarding the response of various aspects during adverse space weather. The study looks into reactive power data that were available in the ZETDC archives. Fig. 2 gives an overview of the Zimbabwean power grid connections.

The assessment compares reactive power responses of various substations linking the following substations: Dema, Warren, Kariba and Orange groove. For this study, days with both low and high solar activity were recorded. The solar activity was classified based on the Kp and DST indices. Days with High Kp index and also low Kp value were selected. Fig. 3 shows the Kp and DST plots for 4 November 2021 (High Solar Activity) and 24 August 2022 (low solar activity). These dates were used for the Dema and Warren Substations. The dates chosen to assess Kariba and Orange groove substations are the 4th of November 2021 (High Solar Activity) and 28 April 2022 (Low Solar Activity).

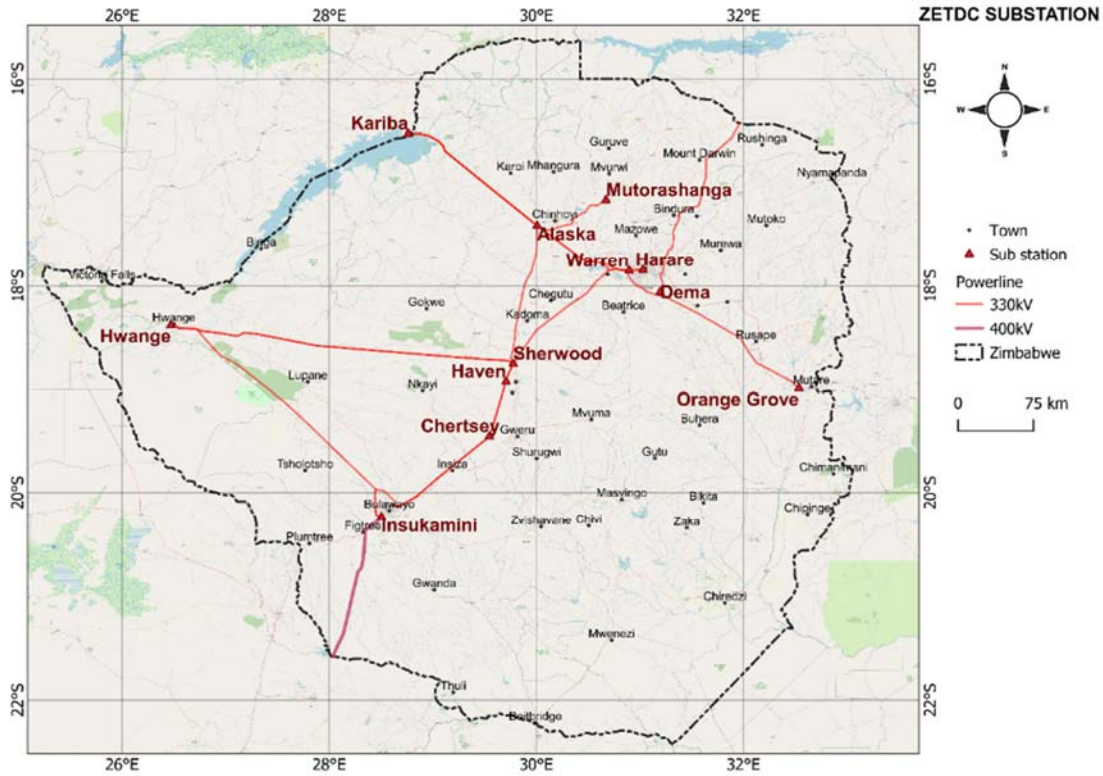

Fig. 2 ZETDC transmission line connections

Four GIC incidents for the solar cycle 25 during the years 2021-2024 will be researched in order to investigate the connections between power network problems and GICs. As we approach the apex of the 11-year solar cycle, it is crucial to do this in order to set the stage for GIC measurements and characterization as Zimbabwe has no records of this study.

Techniques of the Transformer's Reactive Power Loss Due to Adverse Space Weather

When GIC passes through a transformer, the transformer core will produce DC flux. The DC flux and AC flux combine to create a mixed flux. This results in the DC flux adding to the AC flux in one half-cycle and subtracting from the AC flux in the other half-cycle [20]. While the flux of the other half cycle, or the half-wave saturation [21], [23], is weaker, the saturation degree of the core in the half period is compatible with the direction of the GIC grows significantly. The positive and negative asymmetry of the excitation current is caused by half-wave saturation flux. The transformer's half waveform is

currently operating in the saturation zone, which causes the excitation current to be distorted and raises its magnitude [22]. The excitation current of the 90° trailing system voltage is what causes the transformer's reactive power loss. In typical operation, transformer reactive power loss is minimal. However, half-wave saturation brought on by the effects of a geomagnetic disturbance causes the excitation current value to be higher than it would be during normal operation, which significantly increases the transformer's reactive power loss as GIC rises. As a result, the value of GIC and the reactive loss of the transformer are inversely associated. The higher the GIC, the larger the reactive loss of the transformer.

III. Results and Discussions

Data were analyzed for 4 geomagnetic storm dates on four transmission lines substations.

Fig. 3 shows transmission lines within the same vicinity:

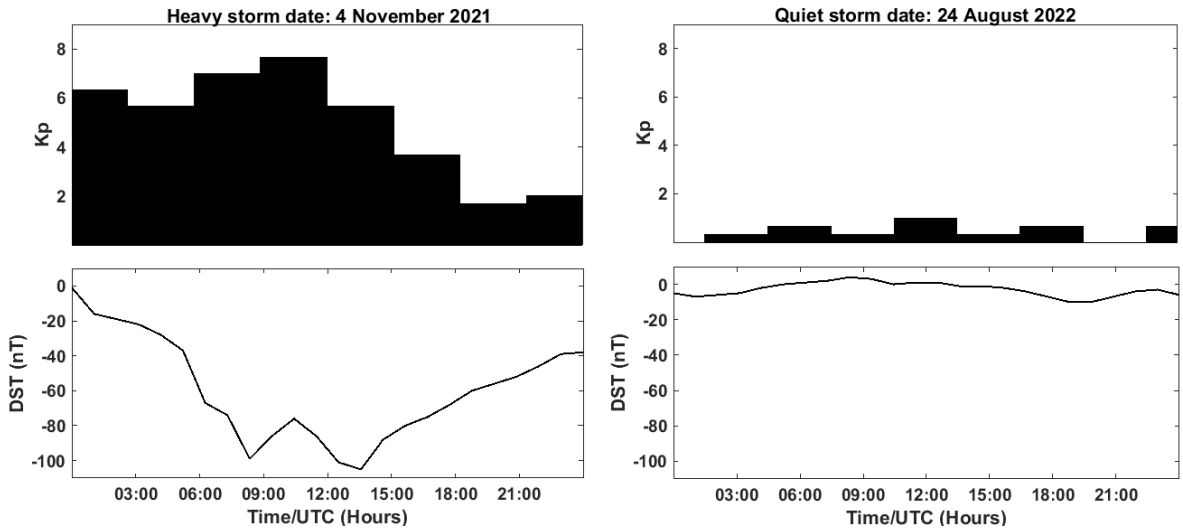

Fig. 3 Kp and DST index analysis

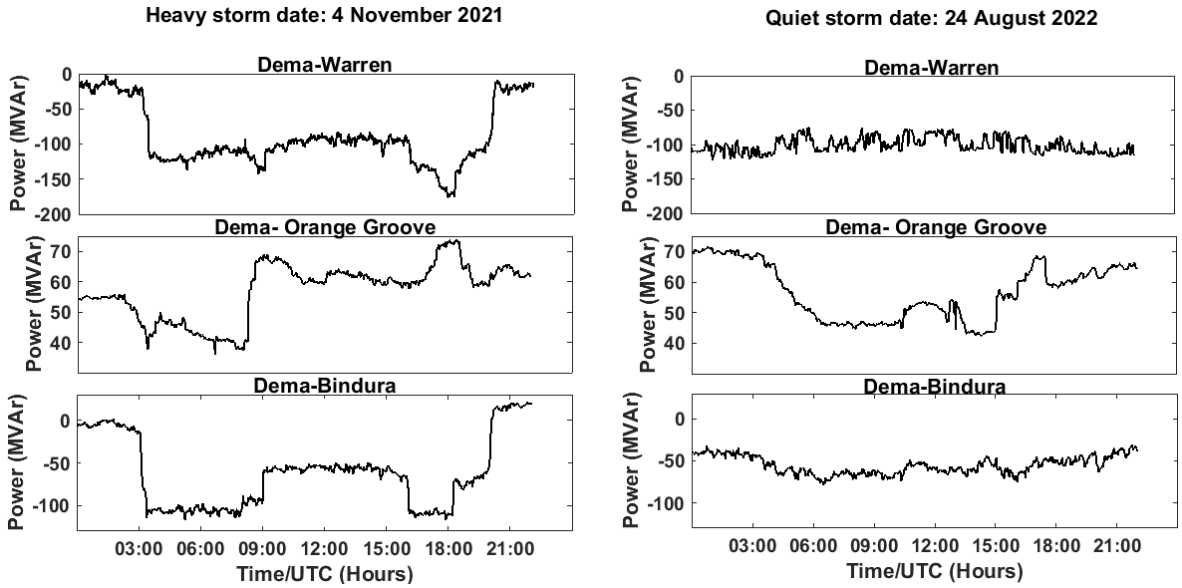

Fig. 4 Analysis of Dema 330KV transmission line

Fig. 3 shows the Kp and DST indices recorded. The 4th of November started with a Kp index of above 5 and reached its highest index, 8, recorded between 0900hours and 1200hours and highest DST index recorded being -105nT. The quiet storm date, 24 August 2022, had a maximum Kp index recorded as 1 and the maximum DST index as -3nT.

The transmission line from Warren to Alaska and Dema had a deviation of 14.89 MVA and 21.32 MVA respectively. The smallest deviation was Warren-Harare transmission line which was 8.11 MVA. Warren transmission lines to Dema and Alaska had biggest deviations between quiet and heavy storm. For the Dema transmission line, the largest deviation was noted on the

connection to Warren with a magnitude of 53MVA compared to the Bindura and Orange groove connections.

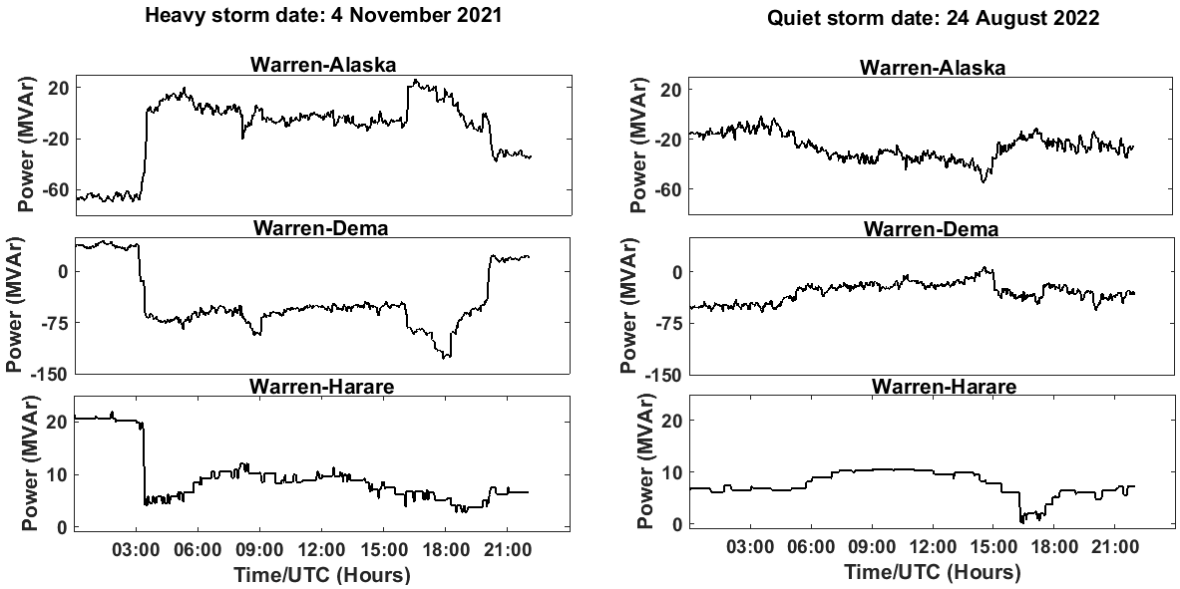

Fig. 5 Analysis of Warren 330KV transmission lines

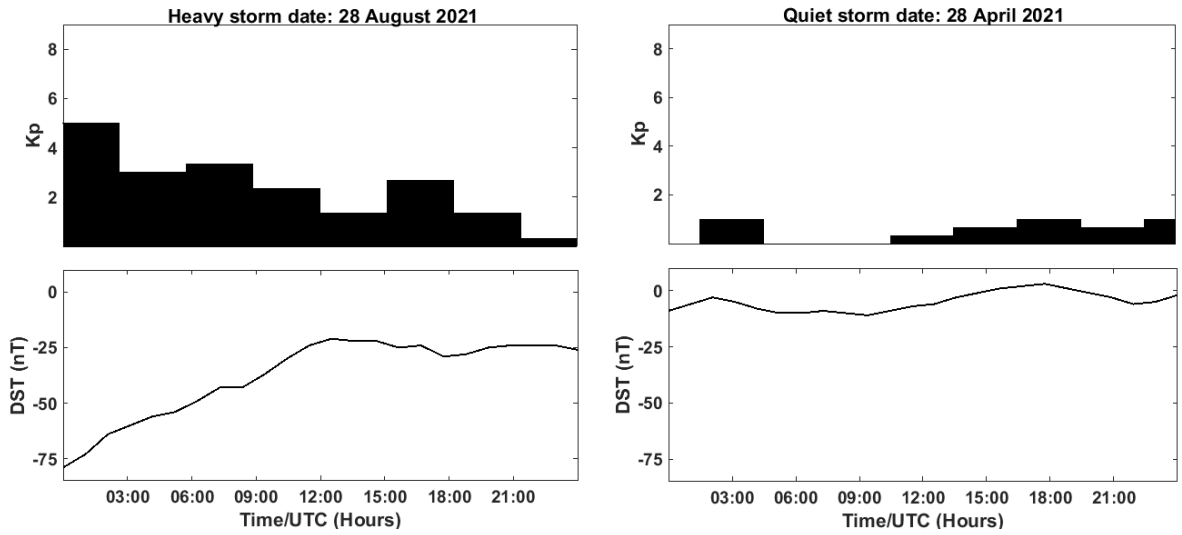

Fig. 6 Kp and DST index analysis

TABLE I
WARREN 330KV AND DEMA 330KV REACTIVE POWER ANALYSIS

	Heavy storm date: 4 November 2021 Highest Reactive power recorded/MVA	Quiet storm date: 24 August 2022 Highest Reactive power recorded/MVA
Warren-Harare	21.51	13.4
Warren-Alaska	-69.98	-55.09
Warren-Dema	-128.14	-59.35
Dema-Orange Groove	73.81	71.31
Dema-Warren	-175.95	-123.05
Dema-Bindura	-116.73	-78.3

Fig. 6 shows end of the transmission line and power line station.

Fig. 6 shows how the 28th of August 2021 began was a high Kp index of 5 and DST index of -79nT recorded and decreased as the day progressed. The quiet storm date, 28 April 2021, had a maximum Kp index recorded as 1 and the maximum DST index as -10nT.

Kariba 330KV substation is stationed at a hydro power plant and has transmission lines from the power station. Kariba 1 and Kariba 2 had a reactive power deviation of about 30 MVA from the quiet day to the heavy storm date. For the orange groove station, on a quiet storm date the reactive power is stable alternating between 0 and 2. On the heavy storm date the reactive power is fluctuating by more than 15 MVA from 0 MVA.

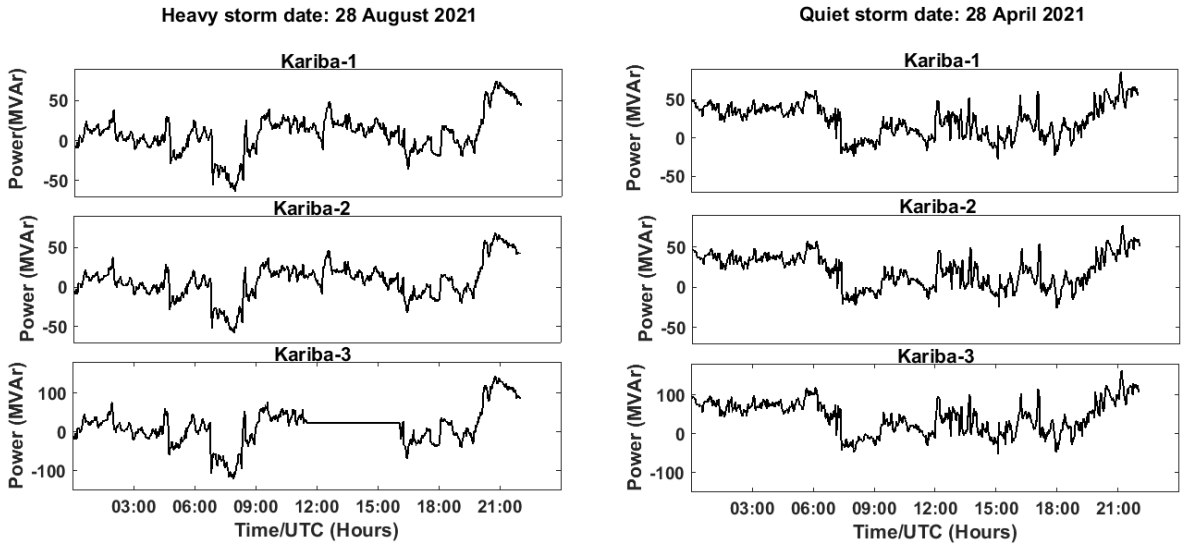

Fig. 7 Analysis of Kariba 330KV transmission lines

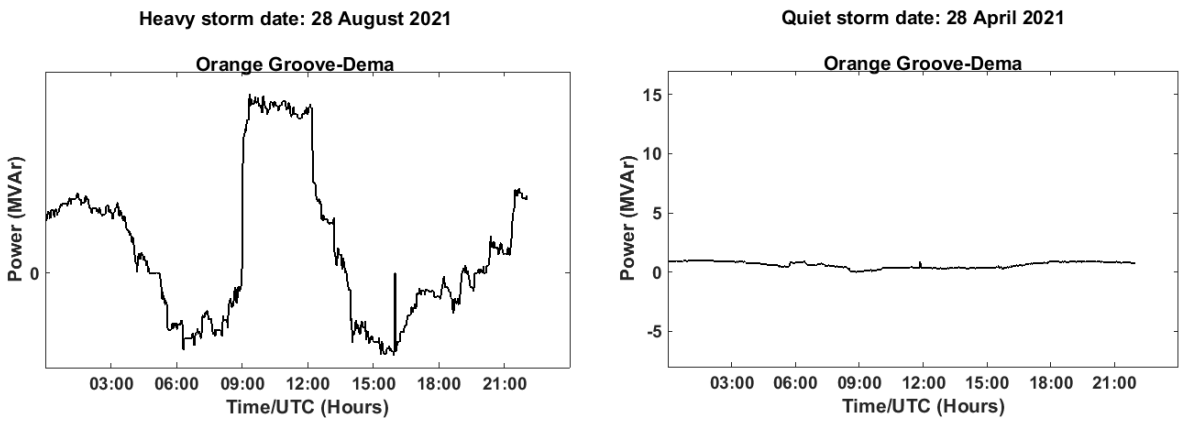

Fig. 8 Orange groove transmission line

TABLE II
KARIBA 330KV AND ORANGE GROOVE 330KV REACTIVE POWER ANALYSIS

	Heavy storm date: 28 August 2021 Highest Reactive power recorded/MVA	Quiet storm date: 28 April 2021 Highest Reactive power recorded/MVA
Kariba-1	-57.8	-26.02
Kariba-2	-64.04	-26.88
Kariba-3	-121.79	-53.04
Orange groove	15.6	1

IV. CONCLUSION

Power grids respond to GMDs, as shown by the agreement of the waveforms of the reactive power response values with the planetary geomagnetic disturbance index. Large reactive power variations arise from voltage imbalances which can result in overheating of equipment, increased hotspots and interference with power quality. The severity of the geomagnetic storm is directly correlated with the reactive power disturbance. Transformers will lose reactive power more frequently as a result of a stronger geomagnetic storm, which will result in a bigger reactive power disturbance of the power system. From the analysis from orange groove, it can be said that transmission line at the end of the line is more susceptible to effects of adverse space weather. Disturbances were noted where the Kp index was high and if they were changes in reactive power. To further pursue this study, it is recommended to install current measuring probes on the earth of the substations. Studies will be noted everyday especially dates where geomagnetic storms occur to note if geomagnetically currents were induced in the earth.

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