# SOLAR CYCLES AND VOLTAGES IN EARTH POTENTIAL

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**Abstract:** In the past few years, solar activity has been a topic of growing concern regarding electronics and power transmission grids. The recent X8.2-class solar flare event in September of 2017 reportedly created geomagnetic storms that bombarded the Earth with charged particles, causing GPS and satellite communication disruptions worldwide. Due to this and past solar flare activity, the subsea communication network community has been imposing stringent requirements for Earth Potential Allowances (EPA) to mitigate possible power fluctuations in high voltage undersea cable networks.
This paper reviews data correlating solar flare events with undersea cable network power feed equipment (PFE) from previously installed systems in order to provide a more realistic evaluation on expected EPA requirements for such systems. Various undersea networks in geographically distinct locations, orientations, and lengths are investigated, providing a global comparison of the effect of severe solar flare activity on undersea cable networks. The resulting analysis provides a realistic, yet still conservative recommended EPA value for undersea cable systems at 0.01 V/km, which is less than half the value currently accepted by industry. Based on this analysis, we propose a new EPA value for consideration by the industry, which will provide design benefits to power starved systems.

## 1. INTRODUCTION

When designing undersea cable systems, an important consideration is the total voltage the system will operate under during system life. This system voltage is determined by three factors: the voltage drop of current flowing in the cable conductor; the voltage drop across each repeater; and finally an allocation of voltage difference between the landing points of the system, the so-called earth potential [1,6,9]. This earth potential allocation is usually a distance-based rule of thumb such as 0.1 V/km.

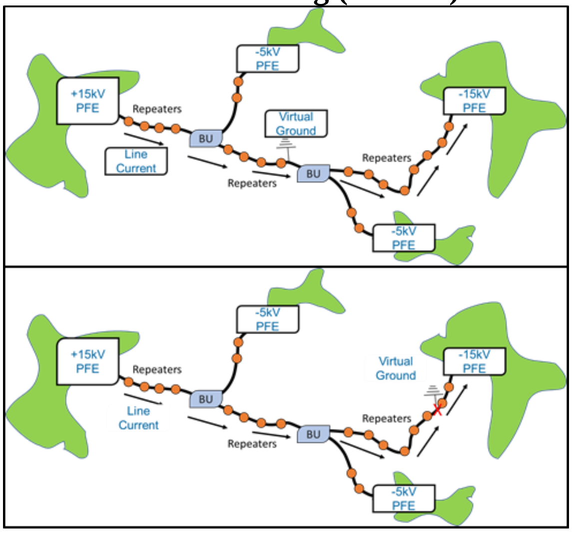
This paper will examine observed earth potential across a variety of system lengths and geographic locations and orientations to determine an appropriate methodology for estimating the EPA. These results will consider various degrees of geomagnetic activity. Finally, these results will be applied to recommend a new rule of thumb of 0.05 V/km as a more representative value to use for earth potential allowance.

## 2. CALCULATION OF SYSTEM VOLTAGE AND OTHER CONSIDERATIONS

The voltage requirements for undersea cable systems are determined by three main contributors: voltage drop across the cable (I*R drop); voltage drop across the deployed undersea bodies (i.e. repeaters, branching units); and the voltage differential between the landing points of the system, known as earth potential. The sum of all these contributors sets the requirements for the power feeding equipment in cable landing stations.

Figure 1a below shows an example of the powering configuration for an undersea system. In this example, the trunk is utilizing 15kV Power Feeding Equipment (PFE) and the branches utilize 5kV PFEs. Under normal powering conditions, the PFEs will Dual End Feed (DEF) to a virtual ground at approximately the midpoint of the system. The PFEs will be operating at half the total system voltage. The PFEs in the terminal stations are sized to support the total system voltage in the event of a fault condition (i.e. Shunt Fault). This is known as Single End Feeding (SEF). SEF improves the system reliability by allowing system powering to be maintained under certain fault conditions.

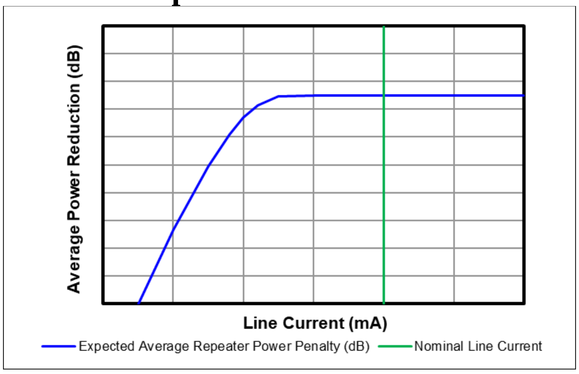
**Figure 1 – a. Normal Powering (Top), b. Fault Powering (Bottom)**




PFE typically operates in current regulation mode. The PFE current is set to the line current required to power the system and the voltage automatically balances to the virtual ground of the system. When a voltage limit is reached, for example when SEF is not supported and a shunt fault occurs, the PFE switches to voltage regulation mode. In voltage regulation mode, the PFE will maintain a constant voltage and the line current will decrease until the proper system powering condition is met.

The most important user of line current in undersea systems are the pump lasers in the repeaters. The power the pump lasers can source directly impacts the system design of the undersea plant. The line current of the system is set such that all pump lasers in the system will source the power required to meet the design requirements, even though some portion of the pump lasers are more efficient than others and require less line current. When the PFE goes into voltage regulation mode and the line current begins to decrease, there is minimal impact on system performance since only a few of the pump lasers are operating below their required line current. Figure 2 shows an example of repeater power reduction vs. line current. It is important to note that even under fault conditions wherein the PFE must go into voltage regulation mode and line current begins to decrease, the transmission performance impact is small until the line current drops enough to cause a larger impact on repeater output power.

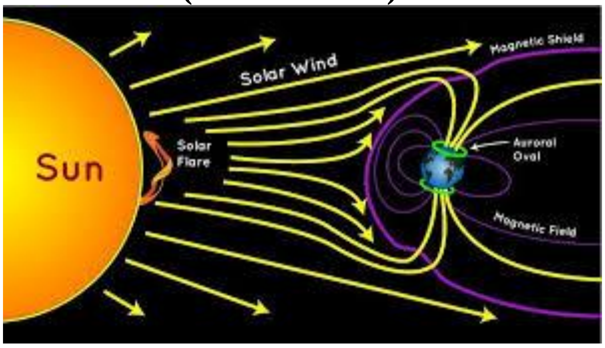
**Figure 2 – Line Current vs. Repeater Output Power Reduction**




## 3. ELECTRO-MAGNETIC INTERACTIONS BETWEEN THE SUN AND EARTH

Beyond the warmth one feels upon the face during a summer day, there is a violent and ever-changing barrage of solar emissions thrust upon the Earth. These solar emissions, also known as solar wind, hurl a large and varying stream of protons and electrons toward Earth. Thankfully, the Earth's magnetic field acts as a shield to deflect this onslaught, as shown in Figure 3. The varying nature of the solar emissions, however, results in changes and distortions to the Earth's magnetosphere. Furthermore, large streams of charged particles can be captured by the Earth's magnetic field, resulting is large electrical currents flowing around the Earth (e.g. auroral electrojets). These variations in the Earth's magnetic field induce electrical currents on the Earth, which can affect the voltage across long electrical systems such as undersea systems or electrical power distributions systems [1,9].

**Figure 3 – Electro-Magnetic Interactions (Credit: NASA)**




The flux of the solar wind is not steady but is influenced by activities such as sunspots, solar flares, and Coronal Mass Ejections (CMEs). Furthermore, solar activity tends to have a periodicity that peaks approximately every eleven years. Examining the impact of a large mass ejection event on installed submarine systems will provide a unique opportunity to examine its affects and possible remediations.

Solar storms have been known to disrupt electrical power distribution systems, oil and gas pipelines and submarine systems. Events such as these and their effects have been documented since the great Carrington observation in 1859, which greatly impacted telegraph systems, the first submarine Trans-Atlantic system (TAT-1), and many others (e.g. L4 system in 1972, TAT-8 in 1989, etc) [2,3,6,7,8,9].

While the impact of these historical events has ranged from significant to insignificant, much has changed in the design of submarine systems to improve the resilience to geomagnetic events. Specifically, PFE is now rated for Single End Feed (SEF) capability, yet the system is operated in a dual-end feed mode, providing a large amount of system voltage margin to absorb geomagnetic effects during a preponderance of system operating life.

A recent solar event occurred in September of 2017 and its affects across a variety of systems was examined to confirm this observation.

## 4. OBSERVATION OF X1 EVENT IMPACTS ON INSTALLED UNDERSEA SYSTEMS

In August and September of 2017, the sun emitted a multitude of significant solar flares and CMEs, which were classified as X-class events and deemed some of the strongest solar flares in a decade by *National Geographic*. Two significant flares peaked on the morning of September 6, with the second classified as an X9.3 flare. Another set of mid-level solar flares were emitted in the early mornings of September 7 and 8, and another X-class event peaked midday of September 10. These flares were part of a series of flares from Active Region 2673, identified in late August 2017, and represent the most intense group of solar activity in the sun's current 11-year cycle. [4]

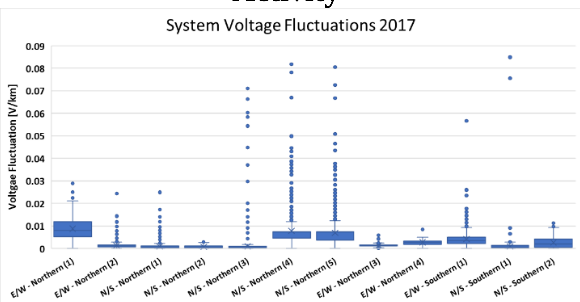
To study the effects of intense solar activity on undersea power transmission lines, shore-end power feed equipment voltage data, collected in 15-minute intervals, were analyzed. Voltage readings during this span of solar activity from August – September 2017, as well as voltage data collected during more recent, non-intense solar activity were studied to make a comparison. In order to obtain a complete view of the solar activity's effect on undersea cable systems, a variety of networks were chosen with geographically diverse locations and varying orientations in terms of power transmission direction. Undersea systems were categorized as either East-to-West (E/W) or North-to-South (N/S) depending on how the powering paths tended with respect to Earth's poles. Systems were also categorized by Northern or Southern hemisphere, depending on which of Earth's hemispheres the systems primarily resided in. Twelve such undersea systems, all installed and commissioned prior to 2015, were designated as "Legacy" systems and were used to study the effects of the intense solar events from 2017. The event activity from 2017 was defined between September 4, 2017 at 12:01AM and September 12, 2017 at 11:59PM. The non-active solar period was defined between February 8, 2018 at 8:15PM and March 9$^{th}$, 2018 at 7:00PM.

Since the absolute voltages of each of the legacy systems varied based on the length and characteristics of the system, the voltage data taken for each system was normalized per the following:

$$V_{fluctuation}\ [V/km] = \frac{(V_{max} - V_{Avg})}{L} \qquad (1)$$

Where L is the specific system length [km], $V_{fluctuation}$ is the voltage fluctuation per kilometer [V/km], $V_{max}$ is the maximum voltage measured [V], and $V_{avg}$ is the average voltage measured [V], all within a given 15-minute interval. $V_{fluctuation}$, or EPA, was calculated for the twelve legacy systems during the solar flare activity events in 2017, and the results are shown in Figure 4 below.

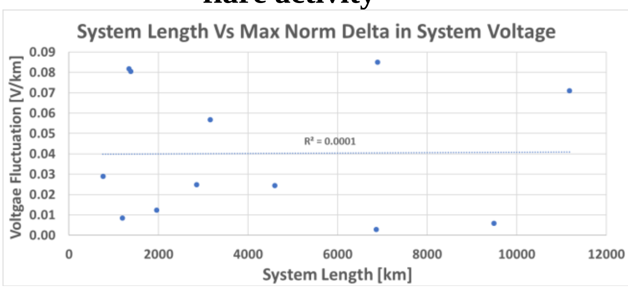
**Figure 4 – Legacy System Voltage Fluctuations during 2017 Solar Flare Activity**




Further observations of the data for the legacy systems shows that the largest voltage fluctuation of 0.085 V/km occurred on N/S – Southern (1) during the solar flare activity. On average, legacy system voltages only fluctuated by a maximum of 0.04 V/km during the solar activity period. Comparing the Northern Hemisphere and Southern Hemisphere systems, the sum of voltage fluctuations per kilometer for the Northern Hemisphere systems was higher, at 0.07 V/km, compared to that of the Southern Hemisphere systems at 0.03 V/km. Additionally, comparing the N/S and E/W systems, it was found that the sum of voltage fluctuations per kilometer for N/S was higher at 0.09 V/km versus that of the E/W systems at 0.01 V/km. Based on this observation, it can be noted that both Northern Hemisphere and N/S systems appear less stable in terms of system voltage fluctuations during solar activity events.

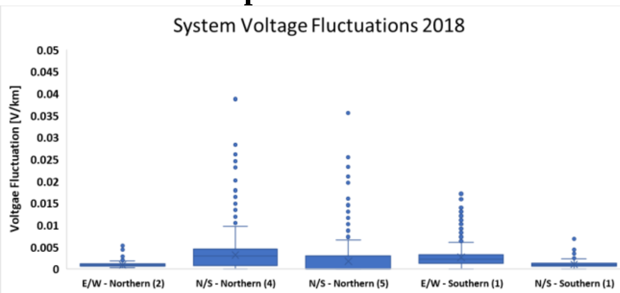
Considering the variety in voltages and lengths of the legacy systems, it is important to determine whether the system length is of any significance to the voltage fluctuations seen during the solar activity period. The voltage fluctuation per kilometer for each of the twelve systems was plotted against the system's lengths, as per the results shown in Figure 5. By examining the data, it can be noted that a linear regression fit for the data yields an $R^2 \approx 0$, which is a strong indication that there is no correlation between voltage fluctuations and system length for these twelve legacy systems.

**Figure 5 – Legacy System length vs voltage fluctuation during 2017 solar flare activity**



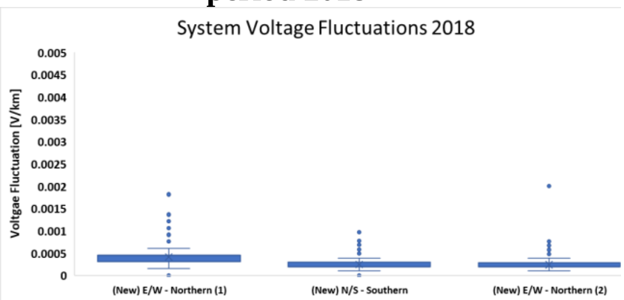

Next, the voltage fluctuation characteristics of these legacy systems were explored by analyzing the voltage data during the non-active solar period in 2018. For this analysis, systems with the maximum voltage fluctuations during the solar flare period in 2017 were chosen as representative systems for each geographic location (Northern, Southern, N/S, and E/W), thus covering the worst case for each region. The voltage fluctuations for the five representative legacy systems during the non-active solar period in 2018 are shown in Figure *6*6 below.

**Figure 6 – Representative Legacy System voltage fluctuations during non-active solar period 2018**




Clearly, the voltage fluctuations experienced during the non-active solar flare period are less than those experienced during the 2017 solar events. Voltage fluctuations on three newer systems, installed and commissioned after 2015, were also studied during the non-active solar period in 2018. The data for these new systems is shown in Figure 7.

**Figure 7 – Newer System voltage fluctuations during non-active solar period 2018**




From this data, it can be noted that the maximum voltage fluctuation experienced on newer systems during the non-active solar period in 2018 was minimal, at only 0.002 V/km on average, and almost an order of magnitude lower than voltage fluctuations measured on legacy systems during the same period. On average, the legacy systems tended to experience a non-zero voltage fluctuation during the non-active solar period, indicating that voltage fluctuations in general may occur in legacy systems due to other factors.[1]

The contribution of these erroneous voltage fluctuations due to measurement error can be removed from the actual EPA for the legacy systems by comparing the fluctuations during the 2017 solar events, and during the non-active solar period in 2018. On average, the calculated EPA for these representative systems during the solar flare period in 2017 was 0.07 V/km, and the calculated EPA during the non-active solar period in 2018 was 0.02 V/km. Taking the difference between the two calculated EPA values yields a realistic contribution to EPA due to the solar activity in 2017 of only 0.05 V/km for the worst case solar flare events in the past 10 years.

## 5. A BAD DAY!

As has been shown, earth potential variations do affect submarine system voltages, however, the key consideration is what is the likelihood of such an event occurring on such magnitude that it will affect the transmission capabilities of the network? At a minimum, a double hazardous state would be required in that the network would be in single-end feed and a large geomagnetic event would occur simultaneously. With an eleven-year solar cycle, and based on historical observations,

[1] Modern PFE are equipped with upgraded A/D converters and precision shunt resistors, which replace the Hall Effect sensors found in legacy PFE. These upgraded components yield an order of magnitude improvement in measured voltage variation over legacy equipment and eliminate the associated gain and offset issues due to geo-magnetic effects.

one could estimate that a single large-scale geomagnetic event could occur during the 25-year design life of a submarine system [5]. Similarly, with proper cable route selection, burial and armoring, one would expect only a few shunt faults at the extreme ends of a cable over the life of a system. The likelihood of both of these occurring during an overlapping period is 1 in 2.7 million, assuming two days geomagnetic duration and fifteen days of operation in single-end feed mode.

## 6. CONCLUSION

While it is clear that geomagnetic activity can impact submarine system voltages, the impact is typically very small, even during large solar events, which are infrequent. Furthermore, most systems are designed to support single-end feeding, but normally operate in dual-end feeding mode, thereby providing a large voltage margin to absorb any variations induced by solar activity. The likelihood of a solar event occurring during a single-end feed condition of the system is negligibly small and does not justify the added expense to design the system for this unlikely occurrence. Our recommendation is to reduce the typical EPA an order of magnitude to 0.01 V/km and utilize the extra voltage for more beneficial uses such as extending single-end feed reach.

## 7. REFERENCES

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