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Risk Analysis for Large Power Transformers in Solar Storms

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***Abstract*— Large power transformers (LPTs) are a vital component of the electrical grid system. Solar flares induce currents in long conductors such as transmission lines that connect LPTs. These currents have caused damage in the electrical grid in the past. Considering that the last major solar flare to hit the earth was pre-electric grid, the grid is unprepared. Therefore, the U.S. economy is at risk from damage. LPTs can be replaced with newer units that can resist damage. The alternatives of LPT replacement versus the null case are compared to show the economic advantages of proactive planning.**

***Index Terms*—Electric Power, Power Distribution, Transformers, Power System Stability.**

I. Introduction

Geomagnetic disturbances (GMD) in commercial electric power distribution result from solar storms. The Sun goes through cycles where it produces sunspots or Coronal Mass Ejections (CMEs) where plasma is released from the Sun into space. The Sun has periods of higher and lower activity called maxima and minima, but even in minima the Sun has sunspots most days. [1]

The peak events are more disruptive to electric power distribution than are the cumulative smaller events. Peak events are rare, and the utilities which are part of the North American Electric Reliability Corporation (NERC) have relatively little experience with solar phenomena compared to Scandinavian countries. One experience was in Quebec Canada during the March 13, 1989 solar storm. During that event, the province lost power for nine hours. [2]

The CME strength for the 1989 Quebec solar storm was substantial. However, it traveled an indirect path to Earth and lost its capacity to damage electrical systems. [3] Very strong solar storms have been measured with modern observation equipment, but none of those storms have impacted the Earth. The storms are generated along a band around the Sun's equator and radially travel out from the Sun, so the Earth has experienced many near misses. The 1859 Carrington Event is an example that shows a very large solar storm can impact the Earth. The effects were observable in telegraph systems throughout the US. Many systems were inoperable.

The probability of a very large solar storm hitting the Earth directly is approximately one percent per year. [4] For this paper, it will be termed as an extreme event. There are long-term observations of the effects of solar flares in nitrates found in ice cores, radionuclide in fossils and lunar rocks, and radiocarbon in tree rings. [5] Some of these records support that Earth could have experienced super-sized solar proton events (SPE) orders of magnitude stronger than extreme events, but if they ever occur, they are even rarer. Current statistical modeling is not suitable for predicting the return frequency of extreme events, let alone super-sized SPEs. [6] Therefore, it is important to understand the possible effects that an extreme event could have on electrical power distribution and the economy.

II. Plasma Dynamics

Solar storms are first visible as sunspots on the photosphere of the Sun. The internal dynamics of the Sun are not well understood, but effort has been made through helio-seismic analysis to model currents in its convection zone. [7]

Sunspots are bulges in the magnetic field, and they contain plasma in the form of electrons and protons. If the magnetic field lines reconnect, then a coronal mass ejection occurs (CME). Depending on the initial kinetic energy of the CME and forces that act on it, it may fall back to the Sun, or if its speed exceeds the escape velocity of 220 km/s, it may proceed outward from the Sun. [8]

There is a correlation between the size of solar storms and their initial kinetic energy. [3] Therefore, even though a storm could take several days to reach the Earth, the most threatening storms would take between half a day and one day to travel one astronomical unit.

Smaller, more common solar storms that reach the Earth might be seen as aurorae near the poles. However, they have relatively little impact on the Earth's magnetosphere.

The greater concern is how electrical power distribution is disrupted. The electrically charged particles that reach the Earth can overpower its protective magnetosphere. Rapid changes in the Earth's magnetosphere induce Faraday currents in the Earth's surface. The electric field that develops in the Earth's surface varies with time and geography. [9]

III. Geomagnetic Disturbances in Transmission

Conductors that touch the Earth's surface develop currents because they have lower electrical resistance than the Earth between areas of opposing charge in the induced electric field. In electrical power transmission, these are termed GMDs, and have been documented at hundreds of amperes in direct current.

The effect on conductors depends upon how long they are because over a longer length, they are more likely to span between locations with greater opposing charges. Therefore, transmission lines are at greater risk.

Large Power Transformers (LPTs) are most susceptible to damage. An extreme direct current can cause the high temperatures that can melt the insulation on the windings. [10] Extra high voltage (EHV) transformers might be more at risk because they tend to be connected to longer lines than other transformers. Temporary disruption can also occur as in the Quebec solar storm of 1989 when blackouts occurred because breakers were tripped.

Transformer design can accommodate measures to reduce the risk of damage to a transformer from GMDs. First, capacitor banks have shown to have some control over direct current flow, but do not appear effective enough. [11] Second, a neutral blocking/bypass device (NBD) can let the high direct currents from ground bypass the transmission and travel on the neutral path to the next grounding. [12] An NBD has three parallel paths to ground including one with a spark gap that allows for overvoltage discharge.

IV. Estimation of Risk

Among the precautions was that the NERC considered creating a database of surplus LPTs so that if some were damaged, they might be replaced. However, since transformer design is highly optimized to local conditions, it is unlikely that surplus LPTs could be easily substituted.

Shutting down the electrical grid when warnings are announced is not an effective alternative. There are several difficulties with that. First, the effect of solar storms is not exactly known, but the hypothetical warnings are only that there could be widespread disruptions. Second, the warning time could be as little as half a day, so that leaves little time to plan. Third, power companies will likely want to not shut down a system in advance, but current surges can develop in as little time as seconds. Fourth, although many communication systems are fiber optic and not subject to disruption by GMD, some communication systems are vulnerable. Therefore, automatic control is preferred.

The authors could only find documentation that two LPTs had been replaced with NBD systems, but there could have been more that were unpublicized. [12] Since installing a NBD normally requires replacement of the transformer, the authors consider it unlikely that many LPTs now have these devices. However, LPTs constructed since the date that the bypass technology has become available are more likely to have the equipment. The average age of LPTs are about 40 years. [13]

The risk to the electric grid will be found, and the economic tradeoffs for installing NBDs will be shown. Much of the information used will have to be estimated, and many assumptions will have to be made. A super-sized SPE is highly unlikely during the life of electric grid components and it would be nearly futile to try to protect against its effects. However, extreme events are common enough that they should be analyzed. A worst case scenario will be presented that is roughly equivalent to the 1859 Carrington Event. The results will demonstrate that exact values for the estimates were not necessary in order to make sound economic recommendations.

One assumption relates to the number of LPTs that need to be replaced in order to provide protection against an extreme solar event. We estimate that there are about 2000 LPTs in the US with extra high voltage of 345 kV, and tens of thousands in the range above 100 MVA. [13] We assume 50,000 above 100 MVA. Differing metrics on transformer size are used because of the limits from using data that was available.

In order to exactly analyze the risk of each one, it would require thousands of separate analyses. That is beyond the work of this paper, therefore more assumptions need to be made. We estimate that two thirds of them are at risk from damage based on the fact that northern states are more at risk, and two thirds of the US population lives in areas with moderate to high risk in a worst case scenario event. [14] Therefore, about 1333 EHV LPTs are at risk, and 33,333 lower voltage transformers.

One main set of assumptions deals with the replacement time for damaged LPTs. The normal design, manufacturing and installation process for an LPT is about two years. [13] Considering that surplus LPTs are not available in quantity and matching specification, then under normal conditions it can be expected that a damaged LPT could be out for two years. This can be rushed if there is an emergent need, but other factors will work to slow down the process. For example, if 1333 EHV LPTs need to be replaced all at once in the US, then the manufacturing processes will be overwhelmed and slowed.

The number of LPTs installed in the US each year is roughly 200. [13] This gives an indicator of production capacity. Assuming that each facility has one full-time shift, then they might be able to triple production if they ran three shifts. This would mean that they could produce 600 units per year. Imports can't be relied upon in an extreme event because solar flares can affect other economies in Europe and Asia simultaneously. Even allowing for the possibility of imports, it would take decades to replace damaged equipment.

If the LPTs at risk were replaced now, the cost to do so would be about $10 M for EHV LPTs, and $4 M for other LPTs. The total cost would be $150 B. This is much greater than the current spending on transmission which is about $10-15 B per year now for all aspects of transmission, and about $1 B per year going to transformers. [13]

The U.S. economy as measured as the market value of all goods and services produced is $21 trillion. [15] The potential for economic damage requires many assumptions too. For example, the exact size of the solar storm that would strike is not known. Assuming an extreme event that disrupts power to two third of the population, then the U.S. economy will suffer greatly. Considering the way that modern economies are interconnected globally, shutdown of a plant in one country could create effects through the whole world. It is not beyond reason to argue that the entire manufacturing industry would be shut until new sources of parts could be found. Virtually every sector of the economy requires electric power. Therefore, we are assuming that the total U.S. economy could be lost for a period of time. Considering the difficulties of producing power transformers under those conditions, a two year replacement time for LPTs seems extremely optimistic. However, with that assumption, the U.S. economy could lose $42 trillion.

If an extreme event could cause damage of $42 trillion, and if an investment in modified LPTs of $150 Billion could prevent much of that damage, then treating it like an investment and spending the money now pays back at a rate of $42T / $150B = 280. As mentioned above, the probability of an extreme solar event is roughly 1% per year. Also, the probability in 50 years is 50%. If there is a 50% chance of suffering a loss of $42 trillion, then spending $150 Billion is a very sound economic investment. Even if there is only a 1% chance of this worst case scenario in 50 years, then economically it is still better to prepare for it than to not. Since the probability of extreme events is 50% over that time, then the only issue to resolve is to determine how likely it is that the extreme event would be strong enough that it would cause the projected damage. There is no doubt that a super-sized SPE would go far beyond the damage predicted here, but they are much less common.

It would take several years to replace all transformers that are at risk. Of course, the entire U.S. is not at equal risk. A solar event that is extreme but not the worst case scenario could still greatly affect parts of the country. Therefore, the replacement process should prioritize areas at greatest risk. The factors to consider are discussed. First, magnetosphere disturbances progress from north to south, so in general northern States should be prioritized. However, mid and low latitudes have risk. [9] Second, local water features on the surface and groundwater affects the development of GMDs from CMEs because current more readily flows through water than rock. [16] Third, loss of one EHV LPT could disrupt a whole system, and so they are more important than lower voltage transformers. Fourth, the direction of the linear conductive materials can have an impact on the direct current flow drawn to it. Yet, it also relies upon characteristics of the solar flare, so this makes it hard to predict. Some researchers have attempted to make predictions. [17] However, each analysis uses differing assumptions so it is difficult to compare them.

V. Conclusions

There is no precise way to tell when the Earth will be struck by an extreme solar flare, and no way to exactly estimate the damage. However, a set of assumptions has shown that the damage to the U.S. economy could reach $42 trillion dollars. This could largely be prevented by investing in replacing Large Power Transformers, and the cost is much less than the possible damage that could be done. Therefore, considering that there is a significant risk of eventual damage, there is a very strong economic case for transformer replacement as soon as practical. Considering that northern states are at greater risk, the replacement process should start there first.

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