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Equipment Protection from Geomagnetically Induced Currents (GIC)

A. RAMIREZ ORQUIN, V. RAMIREZ
Resilient Grids, LLC
USA

SUMMARY

This paper discusses considerations about the GIC hardening of the electric power grid, critical infrastructure presently exposed to the deleterious effects of this disturbance. For that purpose, it is intended to analyze key determinants of that security endeavor; the investigation mainly focuses on three factors: first, the difference in nature between these currents as originated from solar geomagnetic disturbances (GMD) or electromagnetic pulse (EMP) late-time shock waves; secondly, the security impact of presumptive EMP knowledge gaps; finally, the potential limitations of US Presidential Executive Orders and enacted Law addressing this phenomenon. Incidentally, while these orders have been proactive and well-aimed, encouraging the installation of GIC-blocking units in the grid, the approach may end up being an incomplete process. Furthermore, as discussed in this paper, it has recently been ascertained by electric utility experts such a strategy is not entirely free from shortcomings; in fact, it might even result ineffective when all elements are factored in. An additional caution arises from considering the technology immaturity associated to some of the devices currently available to the industry, in combination with their high costs and substantial delays to achieve a definite outcome. Moreover, should the program remain depending upon experimental prototypes, it might not only entail a near unsurmountable task but also a deterioration of the composite network system reliability by introducing an insecure state of its own. This paper probes further into a quest for cost-effective alternatives to make the electric power grid GIC resilient with a sense of urgency.

KEYWORDS

EMP, GMD, GIC Mitigation, Blocking Device, Mitigation Device, Grid Security

alberto.ramirez@resilientgrids.com

General EMP Definitions

The International Electrotechnical Commission (IEC) defines EMP as a series of waveforms covering a wide time spectrum from nanoseconds to hundreds of seconds. It has additionally established that three main waveforms are generated from different nuclear generation and atmospheric coupling mechanisms [1]. There are three key waveforms of interest as defined by IEC. The early-time waveform is referred to in the Fig.1 as E1, the intermediate-time waveform is referred to as E2 and the late-time waveform is known as E3 (made of Blast and Heave subcomponents). The pulse widths of the three waveforms are 100 ns, 1 ms, and 100 seconds, respectively**,** with E(t) electric-field peak values of 50 kV/m, 100 V/m, and 40 V/km, respectively.

IEC Extracts

IEC is an international organization which prepares and publishes international standards for all electrical, electronic and related technologies, with a world membership of 90 countries with a lesser number of affiliate member states. Regarding the subject of this paper, it must be minded that a nuclear EMP (NEMP) field test has never been carried out in the Free World; conversely Russia, an IEC member, is the only country which has systematically performed full-scale NEMP tests since 1962, becoming a source of primal data and information for the purpose of EMP definitions and characteristics. Nevertheless, waveform data as depicted in Fig.1, was established back in the twentieth century, and has received minor revisions since [2]. On the other hand, the mentioned IEC member has repeatedly claimed achieving substantial higher magnitudes than the ones of reference; as an example, a citation of 200 KV/m for the peak of the E1 electric field (instead of the 50 KV/m of Fig.1) was reported by the US Government [3].

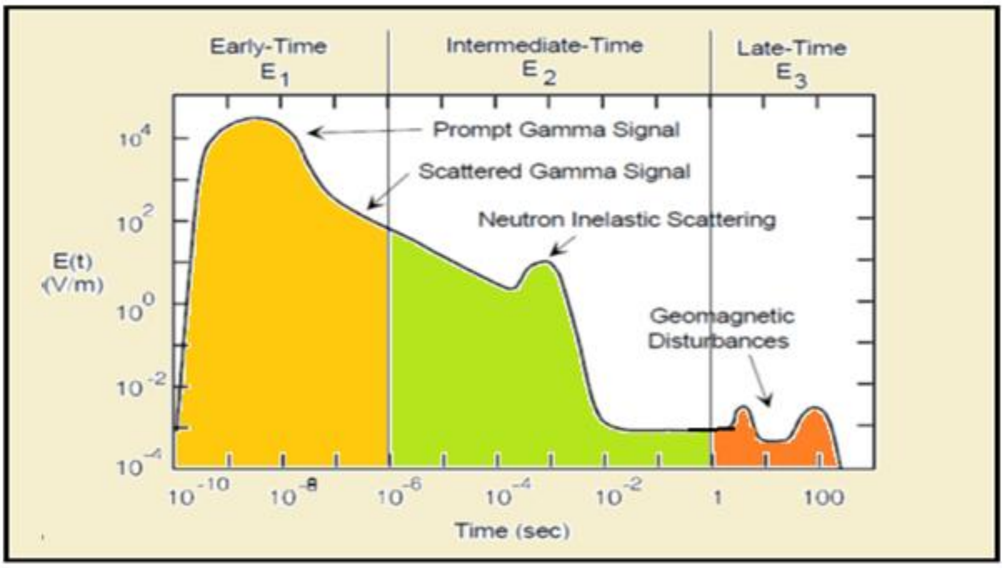

Figure 1: EMP Main waveforms of interest (defined analytically by the IEC)

GIC Basic Considerations

A structural waveform similarity between GIC from geomagnetic disturbances GMD and EMP has been well established, it is also known that surge waves from solar GMD can last for extended periods of time, being predominantly of significant lower magnitudes than the ones generated by EMP. Nevertheless, for this latter case E3 late-time characteristics as depicted in Fig.1, including its shorter waveform duration, cannot be confidently reaffirmed as a basis to make inferences about equipment resilience; this particularly so in view of the repeated claims about the more stressful features reportedly attained for these shock waves.

GMD Operating Procedures and Reliability Standards

Operating Procedures, followed by Reliability Standards have been extensively developed by NERC-GMD Task Force since 2011; in essence, these operational guidelines are multidisciplinary in nature, advancing the ability to deal with moderate geomagnetic disturbances, as has been the case since their inception. That process is primarily based on early GMD alerts, enabling the impact assessment of an incoming GIC via state-estimation computer software; the scheme focuses on grid voltage profile/stability, power transfer, transformer thermal response, etc.; those evaluations, in turn, setting the operational procedures required to optimize a networkwide reactive power reconfiguration/rationing, including plant curtailment or derating to keep the power system in synchronism.

EMP E3 Mitigation Prospect from the Operational Standpoint

Whereas there is in general ample time for solar-storm alerts from agencies as NASA, NOAA, etc., that is not the case for EMP. Certainly, for this latter disturbance it does not seem to exist well-established alerts to enable a viable course of action from the operational standpoint, except perhaps for a last-resort shutdown available within a very short window of opportunity. Most importantly, it must be heeded that the late EMP E3 pulse is preceded by ultrafast E1 and E2 waves; these shocks could well impact utility electric and electronic circuitry, undermining command/control/protection systems. Under those circumstances, any operational alternative may get seriously impaired and thus limited, as stated, to flashing a full blackout; still, such an action would constitute a drastic measure requiring independent system operators (ISO) to make critical decisions; yet in retrospection, resulting in very onerous societal disruptions not necessarily warranted for all EMP events.

GMD Inherent Transformer Resilience

There is a consensus about GMD GIC inherent resilience for typical transformer designs [4,5] that is corroborated by thermal models. This evaluation is chiefly based on tests run by a major manufacturer in a High-power Lab, performed by means of an injection of DC currents (as a close GIC proxy) on an unloaded typical transformer. The results show thermal stability when the excitation is raised up to 200 A. Indeed, based on magnetic circuit theory it is presumable such a stable condition would not substantially change beyond that amperage. Moreover, assuming currents withing the design solar GMD range, their magnitude is normally a fraction of the equipment rated ones, making copper losses not significant when compared to magnetic core losses. Hence, it is conceivable the energy balance to remain mostly invariant; this notion supported from the fact that both components of magnetic core losses i.e., eddy currents and hysteresis depend on maximum flux density and frequency, parameters also staying rather constant after saturation; that appears to be the case for such tests where the unloaded condition is functional to the revealed apparatus thermal stability. Yet, it can be observed that the core loss attained in those cases may have been higher than the common fifty percent of rated transformer total losses.

Further Challenges from GIC

On the other hand, GIC from EMP-E3 can reach levels comparing favorably with apparatus load currents [6,7]. In this case it would not seem plausible to neglect copper losses. In fact, GIC flowing through (auto)transformer windings, could establish sizable DC offsets to the AC load currents and consequently higher than rated copper losses, adding to existing high core ones; this phenomenon brings the possibility of stressful equipment overloads for several minutes, especially when these units operate at full capacity. Additionally, those offset components can be inherently higher and far longer lasting than the well-known DC offsets associated to short circuits; this effect causing unpredictable zero-crossing currents, posing a real challenge to circuit breaker operation and integrity. The extent of these problematic conditions is outside the scope of this paper.

Need for GIC Control

Minding its distinct possibility of damage to major power apparatus [8], GIC magnitude limitation has turn into a matter of endeavor in GMD/EMP power system reliability engineering; as a result, a large number of schemes to suppress this undesired flow has been studied for decades [9]. However, the path to achieve it has not been free from obstacles. In addition, a substitution of that essential heavy equipment is currently difficult due to a very limited world supply, restriction aggravated by the lack of USA manufacturers. Under these circumstances, any mitigation strategy based on an ex-post replacement/recovery is bound to face formidable logistic challenges. Henceforward, the critical importance for suppressing GIC has come to the forefront of interest. In that sense, the guidelines set by Presidential Executive Orders [10,11] and enacted Law [12] have become significant. These orders have been proactive in nature, representing a timely effort; the intended normative includes concerns on the matter of GIC, advocating for a generic installation of blocking units in the power grid.

Potential Challenges to GIC Suppression

The initiatives described above have prompted the industry to a pressing connection of those mitigation devices for purposes of demonstration, proof of concept, testing, as well as providing some protection, albeit quantitatively unknown. In practice, such a scheme has conveyed a sort of tentative process, discretely spotting units in different places of the power grid. Notwithstanding, it has lately been ascertained that strategy is not free from shortcomings. In fact, it may result ineffective or even counterproductive when all elements are considered. For one thing, being GIC caused by high-impact-low-frequency (HILF) phenomena, it is conceivable that consistent results will unlikely be established in a foreseeable future to validate the technologies tried out. But most importantly, a conclusion was recently reached from a thorough and comprehensive research carried out by major utilities, notably by the American Electric Power Company (AEP) [13,14]; that conclusion is best summarized by quoting one of the AEP papers cautionary closing remark: "The effectiveness of a neutral-blocking device is very limited if the deployment is in a small scale". Yet, that emphatic alert seems to apply to what takes place in the national grid from the institutional directives. Furthermore, it can be inferred that any transformer, left in this process with no protective blocking device, could be actually set at a higher exposure to the hazards these induced currents can create. For this somewhat uncharted territory it appears the only risk-averse policy left is bound to contemplate an exhaustive placement of those devices; that translates into thousands of installations.

GIC Mitigation and Sound Electric Utility Systems and Practices

Given that a large-scale deployment of blocking units is imperative to assure the protection of heavy power equipment, several concerns emerge; certainly, technology intended for such massive commissioning must be the subject of a rigorous vetting. Primarily, that course of action is compelled to verify the electric utility record of every device under consideration; in addition, those units ought to exhibit well-established failure modes/rates to attest the transformer banks likely forced-outage-rate (FOR) deterioration caused by their insertion at very sensitive neutral-winding terminals; the issue becomes even more critical in the case of GSU units. Still, the completion of this classic methodology requires a full evaluation of the network composite reliability impact of these devices, providing the standard indices of loss of load probability (LOLP), frequency and duration (FTT), etc. [15].

To Probe Further

It has been established the need for innovative concepts to meet the demanding challenges described in this paper. The electric utility industry ought to keep striving to accomplish a robust hardening of society's most essential infrastructure from GIC threats. With that purpose, security stewards ought to continue pursuing the goal of a cost-effective technology, capable of meeting all constrains without introducing unknown hazards to the system it intends to protect. The outcome of that process should bring about, for reasons discussed in this paper, innovation conceived in simplicity; therefore, a concept substantively free from EMP-vulnerable sensing and switching functionalities; moreover, an assembly embodying few electric utility traditional passive/static components, each one thus vested with well-established failure modes/rates. By these means, the expeditious determination of pertinent outage data for that assembly will be facilitated via straightforward reliability engineering methods. Any technology meeting these attributes shall then have a prospect to achieve the required full grid installation in a secure and timely fashion [16].

Conclusions

An analysis of a comprehensive approach about the much-needed protection of the power grid from GIC has been presented. Furthermore, a discussion of important factors affecting this process was carried out. Some differences between GIC generated by solar GMD or EMP-E3 with their attendant risk implications have been pointed out. Moreover, a caveat is submitted regarding the presumptive knowledge gaps around EMP phenomena and attending risk assumptions; to be particularly minded are the ones impacting equipment resilience, operational postures and recovery strategies. A review has also been carried out on limitations of existing Presidential Executive Orders and enacted Law addressing this important network security; such normative has been well intended, advocating for GIC mitigation by means of a discrete installation of blocking units over the grid. Nevertheless, this paper has referred to the cautionary statement rendered by leaders of the utility industry pertaining to the inherent shortcomings of that strategy when all elements are taken into account. An additional thoughtfulness arises from considering the technology immaturity associated to devices currently available to power companies, with high costs and delays in achieving a definite outcome. What is more, should the program stay the course, remaining reliant on experimental prototypes, in any scale, it might not only entail a formidable task but also a deterioration of the overall composite power system reliability. The paper probes further into guidelines to consider in other to achieve a realistic cost-effective means to protect the electric power grid.

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