21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2017 Grid of the Future Symposium

An EMP Mitigation Perspective: Systems and Components

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

SUMMARY

EMP, in its three basic forms, as well as shock waves from solar flares, denote phenomena which have come to the forefront of interest in the utility industry and society at large. This concern has been reflected in recent legislation addressing this serious security risk to critical electricity infrastructures. This paper presents a basic conceptual engineering standpoint for the protection of the electricity grid from Geomagnetic Disturbance/Electromagnetic Pulse (GMD/EMP) threats. Also, the work represents an analytical proposition about liability concerns associated to each disturbance, postulating besides conceivable strategies to cope with it. The protection of major power equipment is discussed, in particular as it applies to transformer GIC neutral-grounding concepts. In any case, an examination of some characteristic hardware with attending sensing/relaying ancillaries is carried out. It has been fundamental to review the nature and impact these waves impose onto the electric utility infrastructure. Moreover, a revise of basic protection strategies is examined, minding the available set of capabilities, choices and challenges ahead. In particular, a set of considerations of leading GIC-mitigation device concepts is presented. In addition, this work lays down a critical discernment regarding preventative vs restoration approaches as applied to EMP/E1 and E3. For the former, and despite a general perception, this paper supports, from an intuitive economic evaluation, the notion that a balanced ex-ante/ex-post approach can be substantially more cost-effective than the one based on a preventative electrostatic shielding; particularly as applied to all components. Furthermore, it is postulated this venue cannot be considered as a holistic solution to the EMP peril; in fact, no major power apparatus could be seriously damaged from this kind of shock and consequently, a long-lasting grid shutdown cannot be envisaged with any certainty. Conversely it follows, real devastation could come from unreplaceable bulk-transmission equipment damage, as caused by EMP E3 or huge solar GMD; consequently, a priority must be given to a strategy based on hardening such key apparatus to avoid catastrophic events.

KEYWORDS

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

ramirezorquin@aol.com

General

The International Electrotechnical Commission IEC, defines electromagnetic pulse EMP as a series of waveforms covering a wide time spectrum from nanoseconds to hundreds of seconds. It has been established that three main waveforms are generated from different nuclear generation and atmospheric coupling mechanisms [1][2]. There are three key waveforms of interest as defined by IEC. The early-time waveform is referred to in the Figure 1 as E1, the intermediate-time waveform is referred to as E2 and the late-time waveform is known as E3. The pulse widths of these three waveforms are 100 ns, 1 ms, and 100 seconds, respectively**.** The attendant peak values shown can be 50 kV/m, 100 V/m, and 40 V/km, respectively. A central feature of this waveform is that it can expose, depending on the burst height, a very large area of the Earth (on the order of several million square kilometers) simultaneously, as it propagates at the speed of light. This creates a hazard for large-area networks such as the power grid. In fact, it would take a couple of high-altitude bursts to impact the entire continental US. Nevertheless, the most problematic type of EMP wave [3], regarding potential damage to major power

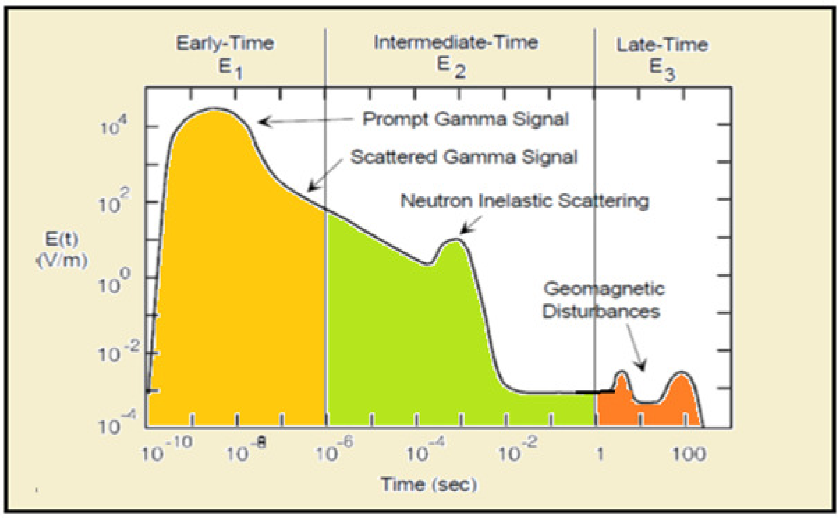

Figure 1: EMP Main waveforms of interest (defined analytically by the IEC)

apparatus can be found on the E3 late-type, This pulse can couple with EHV Transmission lines inducing quasi-DC currents, called Geomagnetically Induced Currents GIC in a similar type of phenomenon as the one produced by solar storms. In general this problem can be divided in two parts: first, EMP/E1 and E2; and secondly, EMP/E3 which includes, by similarity, solar-storm disturbances. The reason for this unfolding stems from the different physical nature of these threats and how they couple into the different components of the power system i.e. solar and EMP/E3 pose a low-frequency medium voltage surge wave, driving a Geomagnetic Induced Current (GIC) through the transmission grid potentially causing deleterious thermal/mechanical effects into major power transformers and shunt reactors; this problem creates potentially a very challenging recovery process, at best. For, in that case, there could be no replacement warehouse stock to resort to; all US firms have lost the manufacturing capability of these large units; worldwide it is very limited as well, with the aggravation of a likely long backlog. Clearly, the recovery approach could not see any viable application and hence, efforts should concentrate sharply on a preventative apparatus hardening.

The Early-pulse Mitigation

In regard to EMP/E1 and E2 shock waves, as aforementioned, it entails dealing with of ultra-fast overvoltage surges. While not directly impacting major power equipment, these are shock disturbances capable of causing insulation breakdown in electric/electronic circuitry, affecting a large number of computer, microprocessors, information/distribution centers with platforms like EMS/SCADA/PLC etc. [4]. What is more, it can pose a similar deleterious effect upon distribution lines and transformers.

Whereas no underestimation of this kind of peril can be implied, and the possibility of utility system blackouts does exist, any forecast of a long-lasting grid devastation is questionable. In fact, no specific EMP full-scale testing has ever taken place in the free world, hence there is no basis to predict an apocalyptic outcome. In any case, this disturbance has theoretically the potential of impacting, more or less severely, thousands of installations with millions of components of very diverse nature, technology and vintage. A preventative attempt to harden each item would consequently result in an unsurmountable task. Nonetheless, there is an inherent built-in hardening taking place anyway as new or refurbished hardware constantly merges into the existing utility plant. However, and yet more significantly, E1 or E2 shocks do not couple with EHV transmission lines and hence cannot damage major power equipment [5]. On the other hand, one common strategy for EMP/E1 protection postulates a full electrostatic shielding of every control center/room; but, several shortcomings to this proposition can be envisaged: first, doing it effectively will impose an exorbitant cost; secondly, it will still leave distribution lines and distribution transformers fully exposed anyhow. In this case, a combination of ex-ante/ex-post strategies may be considered more cost effective, whereby selected key components are primed for hardening in combination with basic shielding implementations; the scheme would be completed with a comprehensive stockpile program. In most cases each control center must carry a full duplicate backup, as it has already turn out to be common practice. Nonetheless, it must be pointed out that for both perils the surge arrester/suppressor, in combination with a systematic application of fiber optics, discrete electrostatic shielding and continuous grounding technologies can be considered primary options to be relied upon to achieve the preventative protection stage; equally important remains a thoroughly planned recovery process. Additionally and, conversely to the power transformer case, spare electronic component/parts for this case are in general readily available, serviceable and affordable. Even so, whereas computers came to improve and greatly optimize the operation of all systems, it may be argued that bare essential functions could still be carried out with precarious electronics as it has been the case in the past for the electric utility operations, aviation, navigation etc. As NASA achieved a historic success with the Apollo Project, counting on limited electronics and computer resources, it can be expected the grid to primitively operate under an EMP-caused similar elementary conditions. This would likely keep the lights on while basic infrastructures develop into service as the recovery process gets underway.

Mitigating Geomagnetically Induced Current (GIC)

As the long track record of solar activity and its similarities with EMP/E3 indicate, a solid prevention of long-term blackouts of this type becomes a sensible policy. Indeed, a program can be based on a robust plan that primarily concentrates on hardening the key grid power transformers. Such a program must be, anyhow, complemented with cost-effective ex-post/ex-ante strategies to cover all viable collateral risks associated with EMP. As stated, the flow of GIC currents, by its quasi-DC nature, can saturate the magnetic circuits of major power transformer and shunt reactors generating, among other things, an ample spectrum of harmonics [6]. This phenomenon in turn, can cause mechanical/thermal problems, including vibration and hot spots. In most cases, particularly at high levels of magnetic flux intensity, the incident could be compromising in terms of equipment health index and expected loss of useful life; a permanent outage cannot be ruled out either. This is the type of threat that must be dealt with and hence several strategies have been proposed.

The Institutional Stance

During 2016 a couple of statues have been generated by both the US Executive and Congress. First, an Executive Order was recently decreed [7]. In addition the CIPA Act has followed. FERC, initially requested NERC and, has recently approved GMDTF's GMD Reliability Standard TPL-007. Nonetheless the institutional stance so far has been about the solar GMD and based on situational awareness in combination with a set of comprehensive operational procedures. The process utilizes an extensive network-wide simulation, equipment monitoring and supervision of transformer response, based on elaborated thermal models. Furthermore, the strategy basically entails a grid apparent power management, in anticipation of a sun-originated Coronal Mass Ejection CME arrival; this procedure taking place after warnings issued primarily by NASA and NOAA. Moreover, a parametrical estimation of the meteor gets carried out, including GIC magnitude and attendant circuital-trace distribution. With this data, the potential voltage response and transformers thermal impact is ascertained. Lastly, an overall evaluation of both active-power derating and reactive-power rationing/optimization of the system is carried out; this process may finally reflect as constraints over power plant outputs and load flows in order to primarily preserve both synchronous and voltage stability. It must be stated that no attempt is made by this normative to control/block the GIC current in order to diminish its magnitude; also that this standard does not and cannot have an application to EMP shockwaves.

A Stakeholder Stance: GIC control

After the severe 1989 solar storm, causing power blackout in Quebec, an endeavor was concerted in order to produce mitigation means to cope with this peril. A primary countermeasure to consider, as Hydro-Quebec carefully studied, hinged around series-compensation means [8]; however this approach, an inherent perfect GIC blocker, is only possible when its viability gets first established from a transmission expansion standpoint. Nevertheless, when that option is not feasible, other arrangements must be examined. A prime proxy to consider, minding the GIC flow follows a quasi-zero-sequence circuital pattern, becomes a transformer neutral component having the capability to reduce or block that circulation. It is worth mentioning that in the past century a first product of this effort i.e. the neutral grounding capacitor, was the first and sole mitigation approach available to the industry [9]; this concept was embodied in various arrangements by different inventors.

Capacitor GIC-Blocking Schemes

A classical scheme consists of a condenser bank in parallel with a surge arrester for ground-fault protection, as shown in Figure 2; this composition somewhat derives from the series-condenser typical design, whereby a metal-oxide varistor MOV bypasses the capacitor for short-circuit protection/reinsertion. Figure 3 depicts such a basic neutral-blocking alternative whereby the ground-fault protection is alternatively carried out by means of a spark gap. It must be stated that, for the analogous series-compensation case the MOV unit still carries a parallel spark gap as a backup. Even

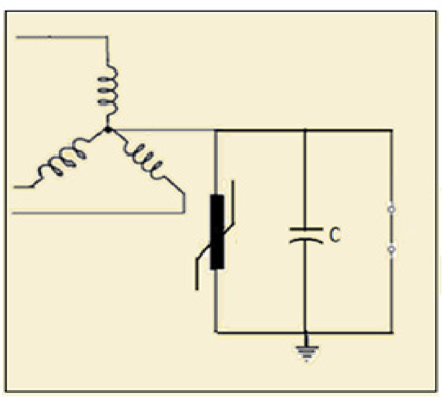

Figure 2: Capacitor GIC Neutral-Blocking Scheme

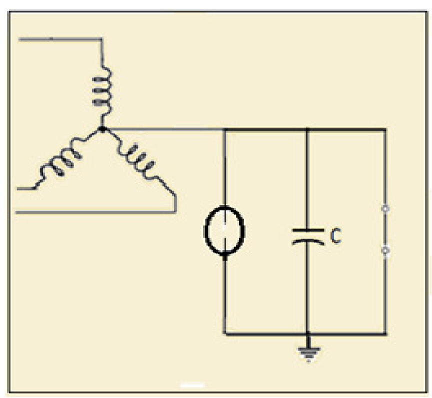

Figure 3: Alternative Capacitor Device Scheme

so, a sole/primary protective functionality from the latter, intended for ground faults, learns to be avoided, since the gap requires a flashover to become conductive, causing thus a sudden wave chopping. This phenomenon, as well known, can generate harmful surges. Additionally, insulation coordination of apparatus with spark gaps has not been established as an electric utility practice. Nonetheless, this issue merits further analysis; for one thing, it has been argued that when the surge arrester operates on a SLGF, it may experience a thermal breakdown followed by a safety valve relief, having to be replaced after the event. That possibility could be considered a drawback, despite the very low probability of a simultaneous ground fault and GIC occurrence. Conversely, a gapless arrester, because of its continuous non-linear characteristic prevents such a wave chopping and its negative effects upon both capacitor and, most importantly, the transformer itself. However, for the scheme of Figure 3 and in particular, a large ground fault would cause the gap to go into a hefty flashover, yet, while no replacement will be required for the unit, a service could still be highly necessitated in order to keep its spark-over characteristic unaltered. A second consideration pertains to the response to EMP voltages impinging upon the transformer neutral end. Indeed, within the GIC condenser-blocking concept, its voltage rating of the unit must be kept under the medium voltage range due to design footprint and cost; this lowers considerably also the attendant overvoltage protective thresholds for insulation coordination reasons. Under this condition, irrespective of having chosen an arrester or spar-gap scheme, a potential high-magnitude EMP blast could conceivably cause its delayed GIC to circumvent blocking; flowing thus either through the arrester or into a possible flashover conduction over the gap. Consequently, the capacitor will be impaired of rendering its very critical application.

Resistor GIC-Reducing/Blocking Concepts

An alternative to the neutral-blocking capacitor can be found on neutral-grounding resistors. This comes to be an attractive option given the simplicity and passivity of these components. For this design, as shown in Figure 4, what is only targeted is a reduction of the GIC magnitude through the transformer; the basic arrangement is shown in Figure 4. For the case of solar GMD, this reduction is deemed satisfactory. Furthermore a low-ohmic version has been proposed whereby it can be connected to the transformer neutral in a self-standing mode, with no requirements for a ground switch, nor

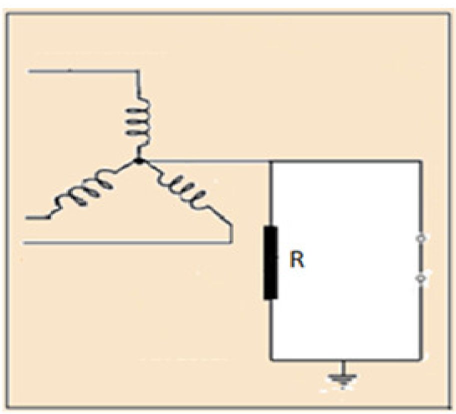

Figure 4: Resistor Mitigation Device

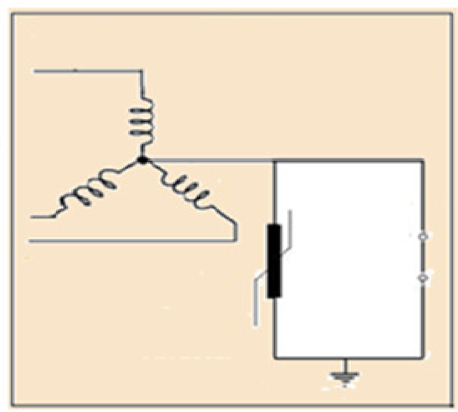

Figure 5: Surge-Arrester Device

affecting the apparatus grounding ratio [10]. The application of this concept has, however, a number of limitations; for one thing the GIC reduction rendered may be insufficient for EMP applications or severe solar storms. But, a most important reservation remains, as is always the case for resistors, from energy

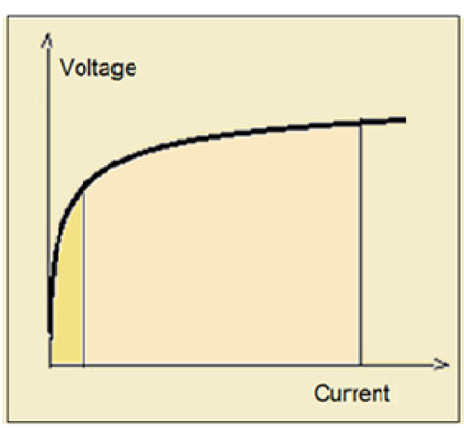

Figure 6: Typical Volt-ampere characteristic of metal-oxide Surge Arresters

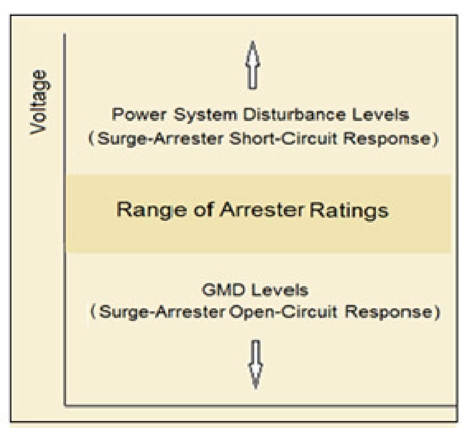

Figure 7: Comparative of Transformer of Neutral Voltage Ranges

dissipation issues, even for infrequent and short deployments; these concerns relate to the strict standard ten-second rating limitation. Indeed, in the case ground faults, particularly for the ones cleared in backup time, the energy dissipation required can be substantial, even when protected by surge arresters; this is more significant as the resistance value increases [11]. In addition, the phenomenon described would impact similarly any resistor disposed in series with neutral-blocking capacitors for the purpose of damping potential ferroresonant oscillations.

A non-linear Resistor GIC-Blocking Concept

In order to deal with some of the issues previously mentioned, a surge-arrester scheme was introduced, as shown in Figure 5. The concept takes advantage of properties typical of zinc-oxide arresters. Such a functional relationship, is depicted in Figure 6, which is termed negative volt-ampere characteristic; this attribute affords both protective and blocking properties, depending on the magnitude of the impinging transformer-neutral voltage [12]. On this basis, a comparative chart, as shown in Figure 7 of that transformer-voltage ranges can be presented for analysis and design of this important dual functionality. This approach resembles in simplicity and straightforwardness the one based on a low-ohmic resistor, without most of its shortcomings, allowing thus a sort of generalized individual transformer surge-suppressing philosophy. A distinct advantage can be derived from this concept; as stated, when either capacitor or linear resistor elements are used to control GIC, the voltage rating of these components must be kept in the low to medium range for cost/size reasons. This constraint does not exist for this concept, allowing the selection of considerable higher surge-arrester ratings, thus enabling a substantially more robust performance. Anyway, the mitigation-device testing program specified by the aforementioned institutional normative will become essential to actually vet all concepts in order to achieve the much needed protection before EMP E3 and Solar GMD.

Probing Further Technical Issues: Sensing and Deployment

An additional question for all schemes is the one associated to both the GIC detection and switching of mitigation devices. As well known, these currents being quasi-DC pose, for severe EMP cases, a current-interruption challenge, as required following their detection. Indeed, while present low-voltage DC-breaker could be considered mature, stemming primarily from solar-panel switching technology, that is not the case for the medium-voltage class at all. An innovative approach to effectively deal with this important predicament is required. In that sense, a rationale for this endeavor can be found on the fact that the threat to critical power equipment stems from the EMP most time-delayed E3 component. Additionally, the E1 pulse epitomizes a very significant electric-field magnitude which, while not posing a menace to such major power apparatus, its detection does not presents a major problem from the sensing standpoint; conversely, the complication of generating an actionable signal enabling an early/timely display of mitigation resources becomes quite demanding. In fact, currently GIC sensing is to a large extent, based on three-phase readings and spectral analysis; a tripping decision is then arrived on the basis of a completely developed GIC. This approach becomes questionable for severe EMP/E3 cases whereby not only the current magnitude can be very large but, equally important, the breaking switch may experience DC recovery voltages well in excess of its rated value. These facts greatly conspire against the GIC interruption capability, and with it, the intended deployment of a mitigation device. Conversely, a process based on an early sensing of the EMP-E1 pulse, translated into an actionable signal, could enable an early tripping so as to deploy an E3-mitigation device. The proposed principle would then consist primarily of anticipating the late EMP-E3 GIC before it fully develops, and even then without any further sensing requirements. Under these conditions interrupting the neutral current could conceivably be facilitated and made feasible by means of regular AC circuit breakers with adequate AC asymmetrical breaking rating.

Conclusions

A conceptual engineering perspective on Solar GMD and EMP phenomena has been presented. Also, a review of the nature and impact these waveshocks impose into the electric utility infrastructure has been described. Besides, a revise of basic protection strategies has been examined, minding the available set of capabilities, choices and challenges at play. In particular, a full discussion on leading GIC-mitigation-device concepts has been presented. Furthermore, this work establishes a critical distinction pertaining to preventative vs restoration methodologies as applied to both EMP/E1 and E3. For the former, and in spite of a general perception, this investigation has made a case that a balanced ex-ante/ex-post approach, from an evident economic standpoint, may be remarkable more cost-effective than one based primarily on, for instance, a massive preventive electrostatic shielding of control centers. The latter venue, as postulated herein, cannot be considered as a holistic solution to the EMP peril, leaving critical distribution and transmission assets fully unprotected. Conversely, a real devastation could definitely come from the disabling void left by the unreplaceable bulk-transmission equipment, as caused by EMP/E3 or huge solar GMD; hence, a priority consideration must be given to a strategy based on hardening those critical units to avoid worst-case outcomes. Consequently, a mitigation-device testing-program, in line with the institutional request, is recommended.

BIBLIOGRAPHY

[1] International Electrotechnical Commission. “Electromagnetic Compatibility (EMC), Description of HEMP environment–Radiated disturbance” (Basic EMC Publication IEC 61000 2–9)

[2] International Electrotechnical Commission. “Electromagnetic Compatibility (EMC), Description of HEMP environment–Conducted disturbance” (Basic EMC Publication IEC 61000 2–10)

[3] International Electrotechnical Commission. “Electromagnetic Compatibility (EMC), Classification of HEMP environments” (Basic EMC Publication IEC 61000 2–11)

[4] NERC. “High-Impact, Low-Frequency Event Risk to the North American Bulk Power System” (A Jointly-Commissioned Summary Report, June 2010)

[5] E. Savage, J. Gilbert, et al. “The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and its Impact on the U.S. Power Grid” (Oak Ridge National Laboratory Report, January 2010)

[6] L. Bolduc, J. Aubin, W. Radasky. "Effect of Direct Currents in Power Transformers: Part I, A General Theoretical Approach, Part II, Simplified Calculation for Large Power Transformers" (Electrical Power Systems Research, Vol. 1, pp. 291-304)

[7] B. Obama, “Coordinating Efforts to Prepare the Nation for Space Weather Events” (692 Executive Order 13744, October, 2016)

[8] T. Molinski, W. Feero et al. “Shielding Grids from Solar Storms” (IEEE Spectrum, November, 2,000)

[9] J G Kappenman et al. “GIC Mitigation; A Neutral Blocking/Bypass Device to Prevent the Flow of GIC in Power Systems” (IEEE Transactions on Power Delivery, Volume 6, No. 3, pp. 1271–1281)

[10] J. Kappenman. “Low-Frequency Protection Concepts for the Electric Power Grid: Geomagnetically Induced Current (GIC) and E3 HEMP Mitigation: The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid” (Oak Ridge National Laboratory Report, January 2010)

[11] A. Ramirez Orquin, V. Ramirez. “Addressing Ground-Induced Current (GIC) Transformer Protection” (CIGRE45 Session, Paper A2–110, Paris, August, 2014)

[12] A. Ramirez Orquin, V. Ramirez. “Blocking Geomagnetically Induced Currents (GIC) with Surge Arresters” (CIGRE US National Committee, 2016 Grid of the Future Symposium, Philadelphia, October, 2016)