MODELING ANALYSIS AND DESIGN OF SURGE-ARRESTER DEVICES FOR TRANSFORMER GIC BLOCKING

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Abstract: This paper addresses transformer protection from Geomagnetic Disturbances (GMD) caused by either solar radiations or man-made electromagnetic pulses (EMP) of the E3 type. A simple, cost-effective means to deal with this hazard is reviewed; that technology, broadly based on a surge-arrester functionality to block the undesired flow of such currents in the power grid. Essential overall considerations regarding transformer performance on grounding ratios, state variables for relay-applications, energy dissipation and device switching are discussed. Finally, basic modelling and design fundamentals are presented in order to facilitate the required typical power system simulations. The production of conforming detailed engineering design and specification documents is discussed.

General: As well known, and extensively indicated by numerous world scientific and engineering institutions for several decades now, the GIC circulation can cause a host of utility network problems; those including ominous blackouts and equipment loss of life, or even permanent damage [1, 2]. In that regard, the intrinsic features and attributes associated to a state-of-the-art metal-oxide surge arrester to cope with the problem is primal. Indeed, in addition to the proverbial circuital passivity and universal protective functionality of this component, its non-linear volt-ampere characteristic yet affords a notable inherent versatility which can be taken advantage of, for the purpose of GIC blocking. This formulation is carried out in order to provide a useful GIC circuital blocking property [3]. The response of this non-linear resistive unit to GMD-originated grid SLG faults has been presented previously [4]. Conversely, the quest associated with the aforementioned needs, has produced useful data on mitigation-device protection. In fact, a large number of references describing extensive simulation results and full-scale tests have contributed to the field of neutral grounding surge arrester protection.

Non-linear Resistor Applications in the Power System

The metal-oxide surge arrester, has been a well-established technology of the industry for over half a century; in this context their use has seen a wide spectrum of utility applications, mainly at the transmission and distribution levels.

The Protective Functionality

In addition to transformer and line protection, arresters and particularly, metal-oxide varistors (MOV) have been extensively utilized for series-capacitor protection [5]. Besides, most neutral blocking devices use arresters for protection as well as for winding neutral-end protection. This implementation contemplates ground-fault contingencies where the arrester must perform adequately; recent research, as reported, addresses this matter in a comprehensive way [4]. Fig, 1

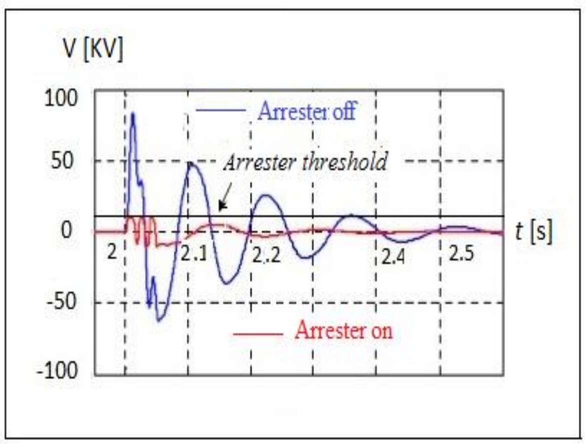

Fig. 1 SLGF Surge-Arrester neutral voltage protection.

shows, a property of relaying-applications invariance after device insertion, while adequately protecting throughout any ground disturbances. A chart from the same reference, as depicted at that same figure, for the case of a SLGF lacking neutral arrester protection (blue plot), and with a 5-KV arrester in place (red plot); the latter proven to be critical for the transformer neutral-end protection of the winding insulation as well as for the GIC-blocking assembly itself. Moreover, the described neutral protection is demonstrated to take place both instantaneously and without causing any voltage-wave chopping. Further vetting has subsequently been carried out by means of a full-scale testing series [6].

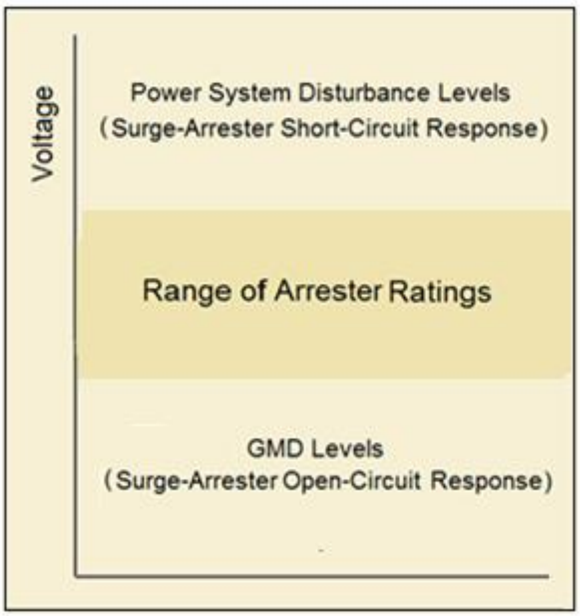

Fig. 2 Comparative of Transformer Neutral Voltage Ranges.

A GIC-Blocking Functionality Principle

On the other hand, minding the extreme non-linear characteristics of the Station-Class metal-oxide arrester, its protective threshold and the transformer neutral-point BIL insulation, a supporting underlying chart of voltage-level ranges can be postulated as discussed below. In that regard, Fig. 2 depicts a graphical comparative of such voltages wherein a distinct surge arrester rating range can be established with the following attributes for a non-linear resistor device as the one shown in Fig. 3:

a) Device presents a response which could be construed as a near-short circuit condition with an equivalent very low resistance from transformer neutral to ground for voltages above the range of application; such an upper interval consistent with ground fault neutral voltage levels and adequate protective margins to coordinating neutral insulation levels.

b) Device presents a response which could be construed as a near-open circuit condition with an equivalent very large resistance from transformer neutral to ground for voltages below the range of application; such a lower interval consistent with GMD-induced neutral voltage levels.

c) As a both valuable and strategic result, an ample in-between (ab) interval of surge arrester ratings can be defined; moreover, this range selection can be regarded to be distinct and satisfactorily ample for a practical set of GMD-mitigation conditions, fault criteria and ground residuals.

The Non-linear Resistor GMD Mitigation-Device Concept

On the basis of the previous discussion a basic GMD-mitigation concept has been established as per the schematic circuit depicted in Fig. 3. A normally-closed grounding switch is connected in parallel with the surge arrester; its operational modes can be precisely monitored and controlled by means of specialized advanced technology, not requiring the challenging DC Medium-Voltage interruption schemes. Yet, it must be stated, such technological application differs as it applies to solar CME or EMP/E3 shocks. For the latter, a sensor microsecond response is required to achieve cost-effective design objectives; this material is outside the scope of this paper. In any case, when those events occur, the ground switch must be opened, inserting the arrester device into the circuit. Contingently, upon this insertion, it becomes a low-resistance bolted path to ground before a potential SLGF. Hence the specification is set straightforwardly, as mentioned, by well-established insulation coordination engineering; this utility practice addresses the transformer winding neutral-end's Basic Insulation Level (BIL), as well as the Basic Switching Impulse Level (BSL) in order to provide coordinated protective margins as set by IEC, VDE, IEEE standards, tests and guidelines.

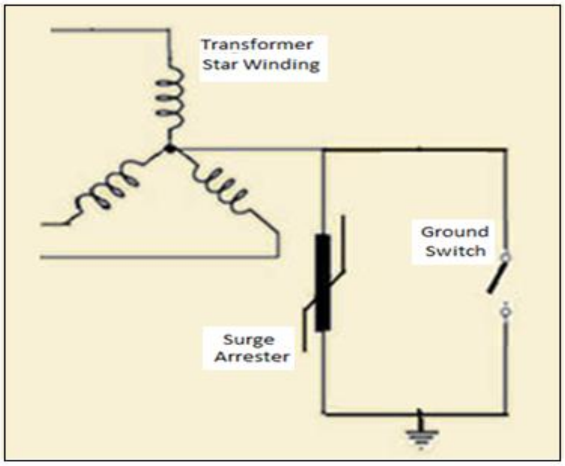

Fig. 3 Basic Non-linear Resistor GMD Mitigation Device.

Device System Performance

A comprehensive evaluation of the non-linear resistor GIC-mitigation device performance, confirming its limited impact upon key operating contingencies from the electric power engineering perspective; was accomplished [3]; that carried out with a full discussion pertaining, not only to the GIC response, but including an extensive energy-duty matrix for a variety of SLGFs. In addition, the blocking feature becomes fully evident given item b) above, as applied to a simple quasi-DC circuit domain. Most importantly was, as pointed out above, the potential for altering pre-existing apparatus/grid circuitry and parameters. Nonetheless, delving further into the issue of steady-state performance is also central for the application of the arrester GIC-blocking device. Indeed, it is a requirement for this unit to have a minimal impact on all AC-state variables and parameters, in particular the grounding ratio X_0/X_1 [7]; likewise, of interest is the potential energy dissipation associated to the arrester device. Notwithstanding, while the primary attribute of having the ability of blocking GIC has been established above, a secondary condition to consider is the flow of residuals to ground through the apparatus under normal/typical operating conditions. In order to address this issue, it is suitable to define and differentiate among the typical apparatus basic characteristics i.e. whether it refers to a transformer or an autotransformer; the latter to be arguably a three-winding unit, grounded Wye-Wye-Delta. Alternatively, the transformer case it is typically represented by a Delta-Wye (grounded) GSU apparatus.

Three-winding Autotransformer

An equivalent circuit for this three-winding autotransformer, predominantly assuming a construction of the shell type or three single-phase units, is shown in Fig. 4, depicting the one for both positive and negative sequence components; Fig. 5 shows the zero-sequence equivalent circuit for a solid neutral-to-ground condition. From short-circuit tests, the low-side short-circuit reactance $X_{L,}$ typically results to be negligible. Moreover, a GIC-blocking surge arrester device insertion between the autotransformer neutral and ground amounts, for

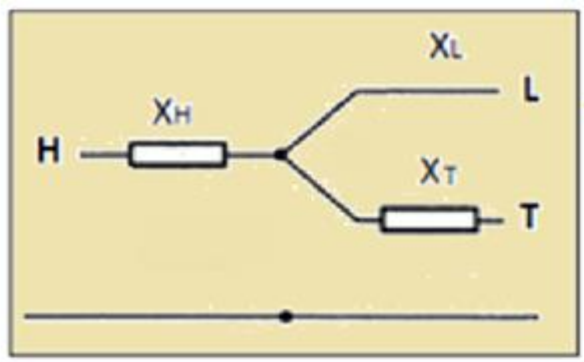

Fig. 4 $Y_gY_g\Delta$ transformer positive and negative sequence per-unit equivalent circuit

normal steady-state conditions, to an open circuit between such neutral end and ground for all state variables, yielding a device voltage drop under the arrester threshold; hence, the flow of GIC currents as well as the AC residuals currents, stemming from the power system will be affected. It must be stated that such a device insertion causes no change on the positive and negative-sequence equivalent circuits; to the contrary, it does cause a change in the zero-sequence circuit. In order to understand that, it is useful to recall that for the particular case of an autotransformer wye-wye, delta tertiary, it does transfer say high (primary) to low (secondary) voltage and power by two different ways i.e. a magnetic coupling (transformer) means and a conduction (voltage-divider) one. In addition, such a voltage divider is composed of a common winding (N_2 turns) plus a series one (N_1 turns). Furthermore, when a blocking arrester device is inserted between the neutral end of the common winding and ground, as depicted in Fig. 6, it bears no impact on either positive or negative-sequence current flows, yet, that winding ceases to be able to conduct either zero-sequence or GIC currents to ground. However, both such currents can still flow from the high-to-low sides by conduction; for the GIC case its flow is through the resistance of the winding; for the

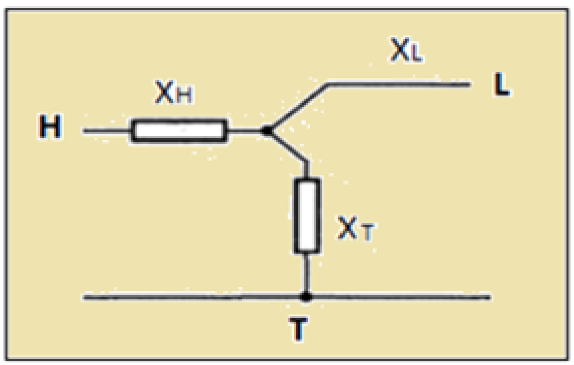

Fig. 5 $Y_g Y_g \Delta$ transformer zero-sequence per-unit equivalent circuit

case of the zero-sequence currents, some additional considerations are required in order to ascertain such a circulation [8]. Actually, the tertiary winding provides the required counter magneto-motive force, as per Ampere's Law, for the ampere-turn equilibrium. Hence, as stated, for this condition the common winding ceases being a zero-sequence conductive path; hence, the unit becomes a two-winding transformer, as shown in Fig. 7, with coupling between the $N_1 I_{H0}$ ampere-turns of the series winding with the $N_3 I_{T0}$ ampere-turns of the tertiary winding. Accordingly, the high-to-low flow of this primary AC current I_{H0} traverses the short-circuit reactance X'_{HT}, as referred to the primary, now associated to the N_1/N_3 turns. While equivalent system parameters can vary, the following reasoning is offered to determine the change in the high-to-low autotransformer zero-sequence reactance; this parameter actually

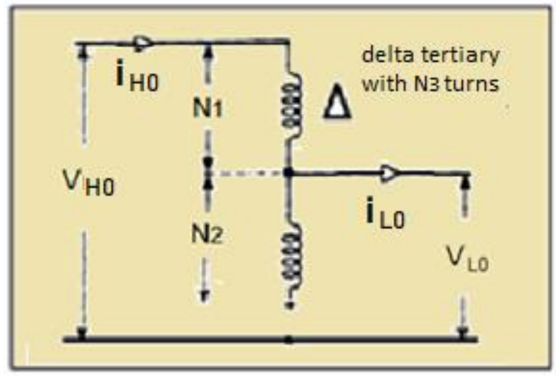

Fig. 6 One-line diagram of autotransformer with isolation from neutral to ground: zero-sequence current flow

changes from the original X_{HL} to a new value X'_{HL} equal to X'_{HT}. Comparing the Figures 4 and 5 with 6 and 7 plus the fact that the associated magnetic circuit, for most construction types, remains basically the same; while the windings turn ratios go from $(N_1+N_2)/N_3$ to N_1/N_3 respectively, thus causing a reduction in the reflected/corrected reactance to the high side by a $[N_1/(N_1+N_2)]^2$ factor. Still, minding also that the original high-to-tertiary reactance is substantially larger than the high-to-low one, both as seen from the high side, a distinctive compensating effect takes

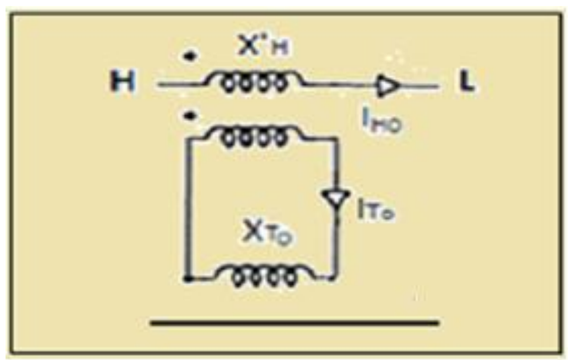

Fig. 7 Zero-sequence circuit of autotransformer with neutral isolated from ground.

place regarding the value of the grounding ratio X_0/X_1. It ought to be recalled that this grounding ratios relate to the flow of the sequence currents through the apparatus, as IEEE defined by the high-to-low transfer sequence-reactance ratios;

those independent of the actual zero-sequence flow mechanism i.e. ampere-turn equilibrium, with or without neutral-to-ground circulation, conduction, a combination of both, etc. (considerations may apply to the GSU transformer case, with the unbalance factors delimited differently). Such a grounding ratio, consequently, in most applications, undergoes only a minor change after surge-arrester GIC device deployment; this in itself becomes a fundamental attribute of this mitigation concept.

Numerical Example

A numerical example is worked out, as shown in Appendix A; it is about the computation of the reactance grounding ratios before and after deployment of the neutral arrester device, as it applies to protect a typical autotransformer, having three windings. Calculations for both Fig. 4/5 and Fig. 6/7 equivalent circuits are carried out. Results indicate that for the steady-state solid ground condition (Fig. 4/5) the computation yields the anticipated typical value of 1.0; furthermore, upon deployment of the neutral arrester device (Fig. 6/7) the calculation of the grounding ratio yields a value of 0.85; actually a counterintuitive small reduction.

GSU Transformer

Conversely to the autotransformer, this is a two-winding transformer case, typically with a large turn's ratio as generator voltage ratings are considerably lower than the associated transmission ones. Furthermore, it is important to assess the nature and impact of ground residual currents in this case. First of all, obviously no such a zero-sequence unbalance may come from the generation side; it could, instead, come from the transmission side due to load or line-parameter unbalances; in any event these latter components are typically negligible [9], moreover it can be said no significant flow is possible through the transformer when and if an arrester device has to be deployed; since, as per item b) above, this latter condition implies the apparatus zero-sequence impedance to be very large and hence any neutral shift would be limited to a Ferranti rise in the zero-sequence network; rise besides stemming from a nil voltage reference at the source end, as well-known, comprised of positive-sequence components only. Hence, the zero-sequence flow is, in general, negligible; besides an arrester device will basically see no real energy duty from the unbalance examination, as long as its rating is correctly specified, and consistent with item c) above.

Modelling of the GIC-Blocking Arrester Device

On the basis of the previous equivalent circuits, simple models can be established to represent the transformers which are GIC protected by means of surge-arrester blocking devices. Two distinct conditions are of interest for power-system studies: first steady state and secondly, the ground-fault conditions.

Steady State

The modelling fundamentals for this condition have been discussed above; it was noted that for positive/negative-sequence analysis, the neutral-to-ground connecting components have no impact on the transformer equivalent circuits. Conversely, the zero-sequence circuit must include the specifics of the neutral-grounding device and winding connections; the equivalent circuits after deployment, for the two typical transformer types considered are shown. Fig. 8 shows the zero-sequence equivalent circuit for a grid autotransformer, while Fig. 9 shows the zero-sequence equivalent circuit for a GSU unit. In the former case, it can be pointed out that

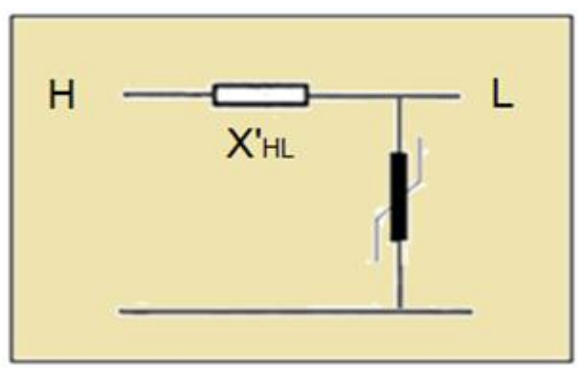

Fig. 8 Autotransformer zero-sequence circuit with surge-arrester device deployed

the neutral-grounding surge arrester device is in a shunt connection with respect to the high-to-low prevailing reactance, whereas, in the GSU case, such a unit short-circuit reactance is in series with the arrester device. For the steady-state unfaulted case, the arrester device sets basically a near-open circuit, causing the autotransformer zero-sequence circuit to remain fairly unchanged from the device pre-deployment state. Moreover, such an arrester device, not traversed by the zero-sequence current, is mostly impervious to it or to its attendant caused line-voltage drop, for typical grid conditions and arrester ratings. In the GSU case, the device open-circuit level renders the transformer temporarily ungrounded. However, as pointed out above, the potential zero-sequence Ferranti-rise effect upon the arrester is unlikely to mount up into an energy duty for typical grid conditions and arrester ratings.

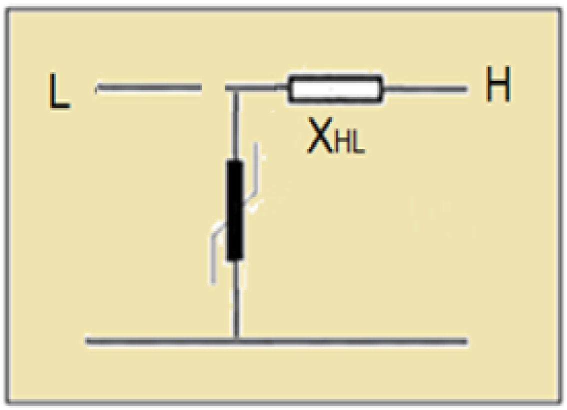

Fig. 9 Zero-sequence circuit of GSU transformer with surge-arrester device deployed

Ground-Fault Response

The SLGF response is different as well for both apparatus construction types selected. As far as the autotransformer is concerned, the fault current does not traverse the arrester device; its voltage gets determined, for the most part, by the low-side line downstream voltage drop to the fault point; should such a magnitude exceed the device threshold level, it would turn it into its activation mode; this, while rare for typical conditions, could lead to a safe valve-relief state. Alternatively, for the GSU transformer, the disturbance is originated by an arcing ground (not SLGF for the very short time of temporary 'ungrounded' conditions); a voltage-zeroing wave surge follows, propagating towards the transformer neutral. In that scenario, reflection and refractions will take place at the neutral node, where the effective arrester surge impedance, in parallel with the two sound-phase surge impedances [10], sustain continuously the protective level as the surge settles at the steady-state value. Fig. 10 shows the timeline sequence from the initial arcing ground to the actual SLGF. This also comprises an added fast neutral-grounding arrester functionality, setting such a fault. Extensive research asserts that, given the energy surge arrester must dissipate, it will arguably go into a safe valve-relief state, setting a contouring external arc. This feature is common to all blocking devices which include arresters, having besides an extensive successful testing record, as stated above. Additionally, surge arresters must comply with IEEE Short-circuit Test guidelines, calling for large safety margins on this application. Moreover, the computation of the external arc resistance yields values indicating neutral voltages to be negligible under SLGF [11].

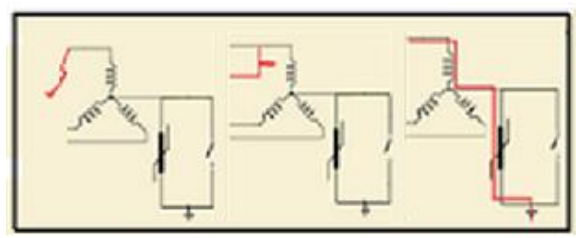

Fig. 10 SLGF time sequence of events for a GSU Transformer

Conclusions

This paper has presented essential tools for a thorough implementation of the GIC surge-arrester mitigation device. In this regard, the surge-arrester unit, typically used for insulation protection of power apparatus, besides being a component associated to a number of known GMD countermeasures, has been proposed as the very sole element committed to suppress the undesired GIC flow through transformers. Indeed, an added innovative functionality to the surge arrester is revealed and presented, whereby it will not only proved adequate in yielding the apparatus neutral insulation coordination, but also providing a fundamental GIC blocking utility. Additionally, this paper develops equivalent-circuit diagrams, showing the basic ones for the scheme hereby introduced. Such a layout, comprising a transformer neutral-grounding normally-closed switch; combination, in turn, capable of timely switching criteria (outside the scope of the paper); nonetheless, the assembly layout gives an outlook of this novel concept's simplicity and imperceptible substation redesign impact. Furthermore, it has reasserted previous independent research about the surge arrester suitability as a useful protective component of GIC mitigation schemes. In addition, it has been confirmed the reliability of transformer neutral insulation protective functionality when that device is deployed. The proposed technology entirely relieves the need for consideration of any exotic/unprecedented blocking schemes based on resistor/capacitor banks, some embodying bulky metallic assemblies, cost and design complexities; context configuring, in turn, a primarily unknown risk exposure. In contrast, and of considerable benefit, the concept introduced here allows for a drastic footprint minimization which could prove significant, minding the space restrictions at most substations, even more critically so for underground installations. In sum, either from a steady-state, current residuals, arrester energy duty, ground faults, parametrical invariance or GIC-blocking, the standalone arrester concept compares favorably with the one based on the condenser bank; nonetheless, without any of its undeniable inherent shortcomings. The difference can only be found at the blocking-function means: one performed by a capacitor bank, the other by an arrester. Subsequently, a basic question arises concerning the incremental cost/benefit of adding massive components, merely to secure the flow of inconsequential ground currents, associated to some GSU transformers. Notwithstanding, it is fair to recognize that any neutral-blocking unit would be able to reduce a percentage of the total GIC of autotransformers; hence again, the question of incremental benefit associated to the alternative use of vast installations, remains quite compelling. Also the presented mitigation approach could help minimizing frequent and onerous GMD-driven, MVAR-rationing operational procedures; these, while stemming from quite elaborated standards, still remain unverified from the very indispensable social/economic scrutiny. This disadvantageous state of affairs, potentially prone to repeating scenarios with cost/benefit erraticism, thus setting arbitrarily winners and losers; that could entirely be avoided by eradicating its single cause: the troublesome GIC circulation in the power grid.

Probing Further

A comprehensive technical documentation blueprint is currently being developed, so as to assist in attaining a thorough specification of the presented scheme for GIC protection, individually focused to every apparatus. As anticipated above, ultra-fast sensing, in combination with advanced switching technology, are essential to cope with EMP/E3 shocks effectively; these features become also significant to avoid, among other things, an excessive dependence on somewhat dicey, unprecedented applications, such as Medium-Voltage DC breakers or neutral-grounding capacitor banks. While substantial progress has been made for over a decade, a thorough testing program of realistic innovative concepts, such as the one hereby proposed, is highly recommended to continue bridging today's treacherous gap on GMD-mitigation assets.

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Appendix A

Numerical Example

Grid Autotransformer Nameplate

500/345/100 MVA
500/345/66 KV
Grounded YYΔ Connection

Test Data

X_{HL} = 0.10 pu on a 500 KV/500 MVA base
X_{HT} = 0.15 pu on a 500 KV/100 MVA base
X_{LT} = 0.13 pu on a 66 KV/100 MVA base

Converting to 500 MVA base yields:

$X_{HL} = 0.10$ pu
$X_{HT} = 0.15 \times 5 = 0.85$ pu on 500 KV/500 MVA base
$X_{LT} = 0.13 \times 5 = 0.75$ pu on 500 KV/500 MVA base

then:

$X_H = 0.5\,(X_{HL} + X_{HT} - X_{LT}) = 0.5(0.10 + 0.85 - 0.75)$
$X_H = 0.10$ pu
$X_L = 0.5\,(X_{HL} + X_{LT} - X_{HT}) = 0.5(0.10 + 0.75 - 0.85)$
$X_L = 0.0$ pu
$X_T = 0.5\,(X_{LT} + X_{HT} - X_{HL}) = 0.5(0.75 + 0.85 - 0.10)$
$X_T = 0.75$ pu

Grounding Coefficient Computation

Steady State

$X_{HLzero\ sequence}/X_{HLpositive\ sequence} = 1$

Moreover after arrester device deployment the turn-ratio correction factor becomes:

$[N_1/(N_1 + N_2)]^2 = (500 - 345)^2/(500)^2 = 0.1$

And the prevailing zero-sequence high-to-low reactance can be computed as:

$X'_{HT} = X_{HT}\,[N_1/(N_1 + N_2)]^2 = 0.85 \times 0.1 = 0.085$ pu

Therefore grounding coefficient for this condition can be arrived at as follows:

$X'_{HTzero\ sequence}/X_{HLpositive\ sequence} = 0.085/0.1$

hence:

$X'_{HLzero\ sequence}/X_{HLpositive\ sequence} = 0.85$

Authors

Vanessa Ramirez has been involved in the energy sector for over twelve years with experience on grid interconnection studies, power system studies for IPPs, ISO's, energy market analysis, and smart grid implementation for a number of distribution systems at major US utilities. She was a Manager for The Structure Group for 8 years with smart grid assignments in the distribution automation and IT DMS areas. Previously she had worked at Navigant consulting as a Senior Consultant were she participated in transmission asset analyses, FERC compliance, and transfer capacity/ interconnection access in the transmission systems. She is the co-author of several white papers, holds US patents, and has authored several articles on energy and sustainability. Mrs. Ramirez earned a Bachelor of Science in Electrical Engineering (EE) from the University of Mendoza, Argentina; and a Master of Science in Electrical Engineering from the University of Texas at Arlington with Summa Cum Laude. She is a Certified Energy Manager (CEM), and is affiliated to the IEEE and AEE (Association of Energy Engineers).

Dr. Ramirez Orquin has over four decades of electric utility experience, starting as a Niagara Mohawk Utility trainee, followed by five years as an application and research engineer at the General Electric AC Transmission Engineering Operation in Schenectady, NY, where he was certified as well on

Surge Arrester Technology. Moreover he practiced for several years in Canada, Brazil, Bolivia and Argentina where he notably served as Senior Advisor to the Secretary of Energy to conduct its National Grid Planning. As an IEEE Senior Member, he was distinguished at the institution's Centennial Meeting by the plenary T&D Committee for his leadership in the emblematical 500 KV Transmission Project. Furthermore, Dr. Orquin had a key role as a co-author and general reviewer of the first edition of the EPRI/ Edison Electric Institute's EHV Transmission Line Reference Book 345 KV And Above, a world standard reference; likewise contributing to the books Operation and Control of Electric Energy Processing Systems (Wiley/IEEE 2010) as well as to the one sponsored by Congress' Task Force on National and Homeland Security, dealing with the electromagnetic pulse EMP threats to our critical infrastructures. Additionally, he has extensively published Transactions and Journal Papers and holds several U.S. Patents on mitigation technology for grid security. In 2007, the U.S. Department of Homeland Security certified Dr. Ramirez Orquin as an Outstanding Researcher. Currently, he serves as a Member of NERC's Geomagnetic Disturbance Task Force serving in its Mitigation-Device Team, as well as a holding membership at Maine's PUC GMD-EMP Risk Working Group and the Florida State Congress EMP Working Group. Dr. Orquin holds a ME from the Rensselaer Polytechnic Institute (RPI), a Ph.D. from the University of Texas (UTA), currently also teaching at the University of Puerto Rico.