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Blocking Geomagnetically Induced Currents (GIC) with Surge Arresters

A. RAMIREZ ORQUIN[1], V. RAMIREZ
University of Puerto Rico
USA

SUMMARY

This paper deals with a mitigation approach to protect transformers from solar storms and electromagnetic pulse waves (EMP) of the E3 type. A simple, cost-effective, means to deal with these hazards is discussed based on a novel surge-arrester Geomagnetic-Induced Current (GIC) blocking principle; this technology is proposed in order to counteract the undesired grid flow of such currents. Furthermore, essential considerations regarding the impact on transformer grounding parameters of neutral blocking devices are presented. Additionally, the application to the power grid (auto)-transformer apparatus of typical design is presented, where it is shown a notable invariance in the applicable earthling ratios after arrester device deployment. Important features presented set a plausible benchmarking with neutral-capacitor devices; a novel remarkable similarity is shown in the GIC blocking functionality with metal-oxide varistor units (MOV). The work requires going through a full examination in order to confirm quantitatively what seemed qualitatively plausible from a typical grid autotransformer having a delta-tertiary winding. Indeed, this ancillary coil has a definite unexpected effect upon the main short-circuit impedances of the transformer, while the surge-arrester blocking device is deployed. Besides, the grounding coefficient, a key indicator of transformer zero-sequence response is analyzed for conditions before and after the proposed blocking device deployment. Such a proposition required also the analysis of the circuital relationships both magnetically and galvanically between windings; in particular, its variation due to the insertion of the proposed blocking scheme in order to arrive at the corresponding grounding coefficients. Moreover, a full discernment around the peculiarities of different transformer types, such as generator step-up transformer (GSU) and transmission grid autotransformer, is offered.

KEYWORDS
Solar Storms, EMP, Surge Arrester, GIC Mitigation, Blocking Device, Grounding Coefficient

ramirezorquin@aol.com

General

It has been established for several decades now, GIC circulation can cause a host of utility infrastructural problems; these including massive blackouts, equipment loss of life or even permanent damage [1]. In that sense, the concept introduced in this paper takes advantage of intrinsic features and attributes associated to the metal-oxide surge arrester to cope with the problem. Indeed, in addition to the proverbial circuital passivity and universal protective functionality of this component, its non-linear negative volt-ampere characteristic yet affords a notable inherent versatility which can be taken advantage of; i.e. via a novel extended purpose. This formulation is carried out in order to provide a useful GIC circuital blocking property; a full discussion of this is presented. The scope of work includes looking at the response of this non-linear resistive unit to GMD-originated voltage surges. On the other hand, the installation of capacitor blocking devices at transformer neutral [2], poses the utility industry with a number of legitimate reservations.

Revisiting Non-linear Resistor Essentials in the Power System

The non-linear resistor, either embodied as a metal-oxide varistor (MOV) or as a 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 electric utility applications, mainly at the transmission and distribution levels.

The Protective Functionality

Notwithstanding, in addition to transformer and line protection, arresters and particularly MOVs have been extensively utilized for series capacitor protection. Moreover, transformer neutral capacitive-blocking devices in general do, for the most part, use also a surge arrester for transformer winding neutral-end protection, as well as for the blocking capacitor unit protection. This implementation contemplates ground-fault contingencies where the arrester must perform adequately; recent work addresses this matter [3], showing besides a system relaying continuum under device insertion, while adequately protecting throughout any ground disturbance.

A GIC-Blocking Functionality Principle

There is a consensus over the nature of the GMD-induced earth potential electric fields as it has been studied by different institutions. Voltage gradients as high as 20-40 V/Km are deemed conceivable in regions prone to severe Solar Storms; additionally there is an ongoing discussion at NERC's GMD Task Force regarding the probability assessment of both geo-electric field and attendant GIC, including a plausible return interval for some specific scenarios. Figure 1 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 Figure 2:

a) Device exhibits a response which could be characterized as a near short circuit condition with an equivalent very low resistance from transformer neutral to ground for voltages above the range of application.

b) Device exhibits a response which could be characterized 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.

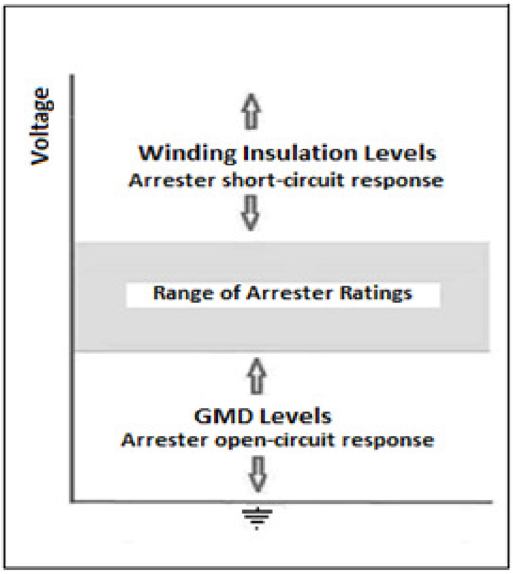

Figure 1: Comparative of Transformer Neutral Voltage Ranges

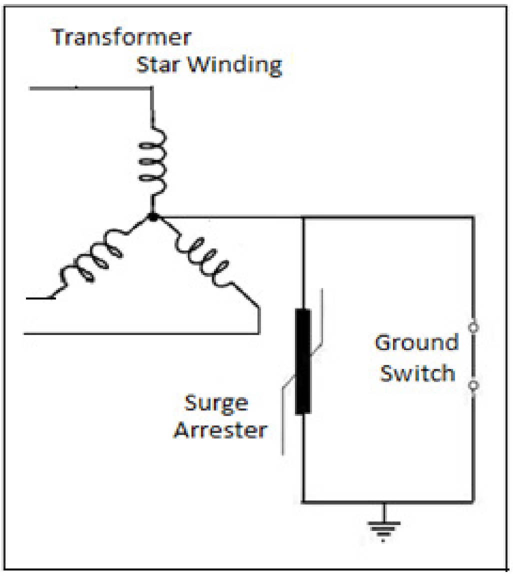

Figure 2: Basic Non-linear Resistor GMD Mitigation Device

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

In addition, it must also be recognized that the unfaulted power grid state does prevail for a very high percentage of the time; nevertheless during those operating conditions there could be sporadic contingencies where the GIC-mitigation device might have to be deployed in a preventative mode; then it would still be some additional considerations to bear i.e. the effect of transformer ground residual currents. Indeed it is an inherent part of transmission line flow to have both negative and zero-sequence components in addition to the positive-sequence one. Moreover, under the b) condition these components are typically negligible [4], whereby the negative-sequence unbalance is of no consequence upon the neutral ground potential; regarding the zero-sequence flow 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) 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. Consequently an arrester device will basically see no real duty from the unbalance examination as long as its rating is consistent with item c) above.

A Non-linear Resistor GMD Mitigation Device Concept

On the basis of the previous discussion a basic GMD mitigation concept can be proposed as per the schematic circuit depicted in Figure 4. A normally-closed grounding switch is connected in parallel with the surge arrester; its operational mode is controlled/monitored by a Hall-effect current transducer CT [5]; for this setting when the quasi-DC current magnitude exceeds a given reference level the ground switch opens inserting the surge arrester in the circuit; such resistive component, with its adaptive negative volt-ampere characteristic, as aforesaid carefully specified according to the given design criteria, to yield a blocking resistance before GIC currents attempting to flow from the transformer neutral to ground.

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 has been carried out [6]. Such a reference presents a full discussion pertaining to the GIC response. In addition, the blocking feature becomes fully evident given item b) above as applied to the 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 upon all AC steady-state variables and parameters, in particular the grounding ratio X_0/X_1; likewise of interest for the potential duty 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 possible apparatus basic characteristics i.e. whether it is 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

A equivalent circuit for this three-winding autotransformer, assuming a construction of the shell type or three single-phase units, is shown in Figure 3, depicting the one for both positive and negative sequence component; Figure 4 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 ranging in value from measured plus/minus 0.2 times the high-to-low reactance, as at test; zero becomes a convenient average to use; coil resistances may be as well neglected facilitating the analysis further.

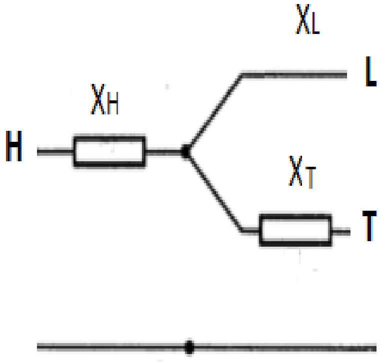

Figure 3: $Y_gY_g\Delta$ transformer positive and negative sequence per-unit equivalent circuits

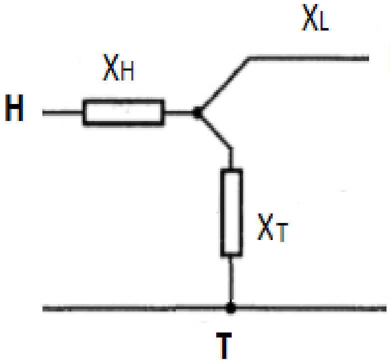

Figure 4: $Y_gY_g\Delta$ transformer zero-sequence per-unit equivalent circuit

Moreover, a GIC-blocking surge arrester device insertion between the autotransformer neutral and ground amounts, for 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 both the positive and negative sequence circuits; conversely, it does cause one in the zero-sequence circuit. In order to understand this change it is useful to recall that for the particular case of an autotransformer wye-wye, delta tertiary, it transfers 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). Besides, when the arrester device is inserted between the neutral end of the common winding and ground, as shown in Figure 5, it has no impact on both positive and negative sequence current flow; yet the winding ceases to be able to conduct either zero-sequence or GIC currents to ground. However, both such currents still can flow from the H to L sides by conduction; for the GIC case its flow is through the resistance of the winding; for the case of the AC zero-sequence currents additional considerations are required in order to ascertain such a circulation. Here, the tertiary winding generates the required ampere-turns for the classical magnetomotive force equilibrium. As stated, for this condition the common winding ceases to be a conductive path of the zero-sequence circuitry; hence the unit becomes basically a two-winding transformer, as shown in Figure 6, with coupling between the N_1I_{H0} ampere-turns of the series winding with the N_3I_{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 zero-sequence short circuit reactance; this parameter actually changes from the original X_{HL} to a new X'_{HT}. Comparing the Figures 4 and 5 with 6 and 7 plus the fact that the associated magnetic circuit remains, for most construction types, 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 reflected 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

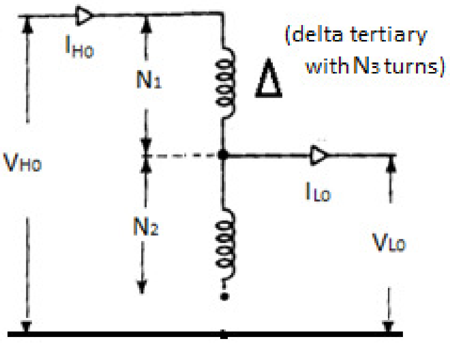

Figure 5: One-line diagram of autotransformer with isolation from neutral to ground: zero-sequence flow.

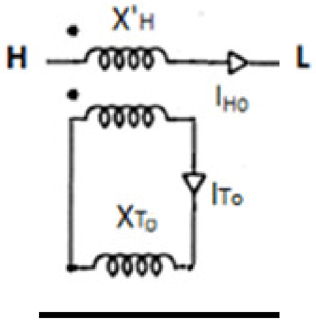

Figure 6: Zero-sequence circuit of autotransformer with neutral isolated from ground

high-to-low one, both as seen from the high side, a distinctive compensating effect takes place regarding the value of the grounding ratio X_0/X_1. It ought to be recalled that grounding coefficients relate to the flow of sequence currents through the apparatus, as IEEE defined, by the high-to-low transfer sequence-reactance ratios; those being independent of the actual zero-sequence flow mechanism i.e. ampere-turn equilibrium with/without neutral circulation, conduction, a combination of both, etc. (special considerations may apply to the GSU transformer case, where unbalance considerations are delimited differently). Indeed, such a grounding ratio consequently, in most applications, undergoes only a minor change after surge-arrester GIC blocking device deployment; this in itself becomes a key remarkable attribute of this mitigation concept.

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, however, come from the transmission side due to load or line-parameter unbalances; in any event these latter components are typically negligible [7], 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. Consequently the zero-sequence flow is, in general, negligible; besides an arrester device will basically see no real duty from the unbalance examination as long as its rating is consistent with item c) above.

Conclusions

This paper has presented the introduction of a substantive conceptual refinement to the classic GIC resistive mitigation device. In this regard, the metal-oxide non-linear surge arrester typically used for protection of power apparatus, besides being a component associated to most 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 has been revealed and presented whereby it will not only prove adequate in yielding apparatus neutral insulation protection but also provides an essential GIC blocking utility. Additionally, this paper discloses a circuit diagram showing the basic arrangement of the scheme introduced, comprising a normally-closed transformer neutral-grounding switch, disposed in parallel with the surge arrester unit; that combination in turn capable of timely insertions according to utility system requirements and criteria (outside the scope of this paper); nonetheless, the assembly layout gives an outlook of this novel concept's simplicity and minimum substation redesign impact. Furthermore, following reference [5] and other independent research regarding the surge arrester suitability as a useful protective component of GIC mitigation schemes; they have as well confirmed a reliable transformer neutral insulation protective functionality when the device gets deployed. Moreover, the proposed technology and method entirely relieve the need for consideration of blocking mitigation components based on full-size power capacitors or linear-resistors, some bearing bulky assemblies, cost, design complexities and undeniable risk implications. In addition and, of considerable benefit, the concept introduced allows for a drastic footprint minimization which could prove critical minding the proverbial space restrictions at most transmission/distribution substations. In sum, either from a steady-state, current residuals, ground disturbances, parametrical invariance or GIC-blocking perspectives, the standalone arrester device compares favorably with the one based on the condenser, yet without any of its undeniable inherent risks. 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, quasi-parasitic ground currents associated to some GSU transformers. Notwithstanding, it is fair to recognize that any neutral-blocking unit would be able to reduce slightly about 50 percent of autotransformer's GIC, hence the question of incremental cost/benefit associated to the alternative use of huge capacitor-bank installations remains quite compelling; in addition, these units are called to operate infrequently. Also the introduced protective approach can help minimizing frequent and onerous GMD-driven preventative operational procedures, mostly implying an undesirable and potentially problematic diversion/overburden to control centers.

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