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Designing Surge Arrester Devices for Transformer GIC Protection

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SUMMARY

This paper relates to the design of surge arrester devices for transformer protection before geomagnetic disturbances, caused by either solar storms or electromagnetic pulses (EMP) of the E3 type. A cost-effective approach to mitigate this threat is examined for a technology based on surge arresters to block the flow of such currents in the power grid. In that sense, the features and attributes of a state-of-the-art metal-oxide surge arrester to cope with the problem are revisited. In addition, the circuital properties of this component affords a distinct versatility, which can be used for the purpose of GIC blocking. A comprehensive evaluation of the non-linear resistor GIC-mitigation device performance is carried out; this in order to confirm its limited impact upon key operating contingencies from the electric power engineering perspective; the work carried out with a full discussion pertaining, not only to the GIC response, but including a full energy-duty matrix for a variety of grid unbalanced faults. Additionally, this paper treats the matter of steady-state performance, also central for the application of reference. In fact, it is a requisite for this application to have a minimal impact on all AC-state variables and parameters, in particular the grounding ratio. Moreover, becomes it of interest the energy dissipation associated to the arrester device under normal conditions. Consequently, while the primary attribute of having the ability of blocking GIC can been established, a secondary condition to consider is the flow of residuals to ground through the apparatus steady-state normal operating conditions. In order to address this issue, a difference is established between two typical grid apparatus; i.e. a transformer or autotransformer. The modelling fundamentals for this condition are discussed via a symmetrical-component sequence analyses, assessing the impact that neutral-to-ground connecting components have on the transformer equivalent circuits. A further insight is required to contemplate that representation with the surge arrester device deployed, both under steady-state conditions, including besides a simultaneous SLGF. A numerical example is presented with such a computation for both equivalent circuits. Results indicate that for the steady-state the grounding ratio gets moderately unchanged from the base case, when the blocking device is deployed; this in itself becomes a novel attribute of the mitigation concept under scrutiny in this paper. A discussion regarding the optimal substation design placing of the GIC-blocking surge arrester is presented.

KEYWORDS

EMP, EMP-E3, GIC Mitigation, Blocking Device, Grid Security, Surge Arrester

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General

As well known, a GIC circulation can cause a number of utility grid problems, including blackouts; some with possible equipment loss of life or even permanent damage [1, 2]. In that regard, the properties associated to metal-oxide surge arresters to cope with that problem are fundamental. In addition, the circuital passivity and protective features of this component, particularly its non-linear volt-ampere characteristic affords a versatility for the purpose of GIC blocking. This formulation is carried out to provide a useful GIC circuit 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 reality, a large number of references describing extensive simulation results and full-scale tests have contributed to the field of neutral-grounding surge arrester protection.

Surge-Arrester Background

The metal-oxide surge arrester, has been an 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. Furthermore, in addition to transformer and line protection, arresters and particularly, metal-oxide varistors (MOV) have been extensively utilized for series-capacitor reinsertion/protection. Besides, most neutral blocking devices use arresters for protection, covering their winding neutral-end as well. This implementation contemplates ground-fault contingencies where the arrester must perform adequately. On the other hand, minding the non-linear

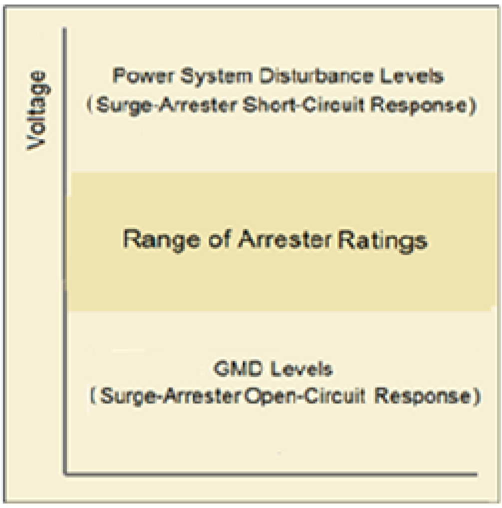

Fig. 1: Comparative of Transformer Neutral Voltage Ranges

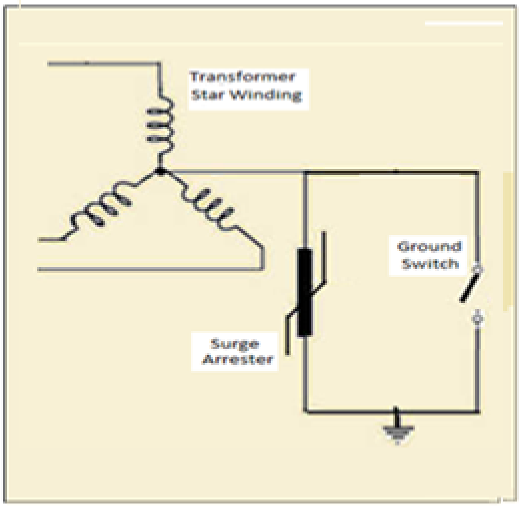

Fig. 2: Basic Non-linear Resistor GMD Mitigation Device

characteristics of a metal-oxide arrester, its protective threshold and the transformer neutral-point BIL insulation, a supporting underlying chart of voltage-level ranges can be postulated. In that regard, Fig.1 depicts a graphical comparative of such voltage magnitudes wherein a distinct surge arrester rating range can be established with the dual-functionality capacity for AC protection and quasi-DC GIC blocking.

Non-linear Resistor GIC-Blocking Concept

On the basis of the previous discussion a basic GIC-blocking concept has been established as per the schematic circuit depicted in Fig. 2. A normally-closed grounding switch is connected in parallel with the surge arrester; its operational mode 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 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 in the circuit. Contingently, upon this insertion, it becomes also a low-resistance bolted path to ground before a SLGF; hence the specification is set directly by established insulation-coordination industry practice.

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 [3], including a full discussion pertaining, not only the GIC response, but also an extensive energy-duty template for a variety of SLGFs. In addition, the blocking feature becomes self-evident. Nonetheless, looking further into the issue of steady-state performance becomes 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 state variables and parameters, in particular the grounding ratio X_0/X_1 [5]; likewise, of interest is the potential energy duty associated to the arrester device. In order to address this issue it is suitable to differentiate the possible equipment basic characteristics i.e. whether it is a transformer or an autotransformer; the latter basically 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, chiefly assuming a construction of the shell type or three single-phase units, is shown in Fig. 3, depicting the one for both positive and negative sequence components; Fig. 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 negligible. 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

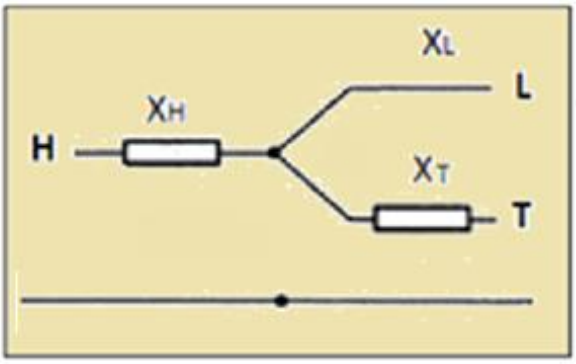

Fig. 3 $Y_gY_g\Delta$ transformer positive or negative sequence per-unit equivalent circuits

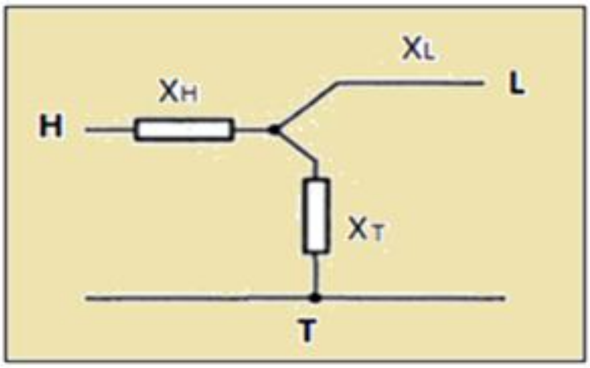

Fig. 4 $Y_gY_g\Delta$ transformer zero-sequence per-unit equivalent circuit

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 residual currents stemming from the power system will be affected. It must be stated that such a device insertion causes no change on the positive or negative sequence equivalent circuits; conversely, it does cause 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 high (primary) to low (secondary) voltage, current 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 the surge-arrester device is inserted between the neutral end of the common winding and ground, as depicted in Fig. 5, it bears no impact on either positive or negative-sequence current flows; yet, the 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 case of the zero-sequence currents, some additional considerations are required in order to ascertain such a circulation [6].

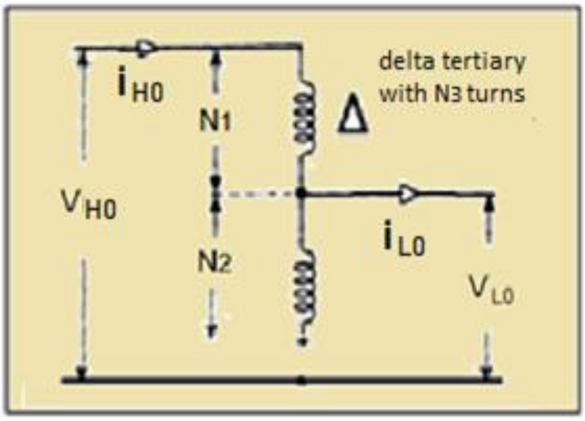

Fig. 5 One-line diagram of autotransformer with isolation from neutral to ground: zero-sequence current flow

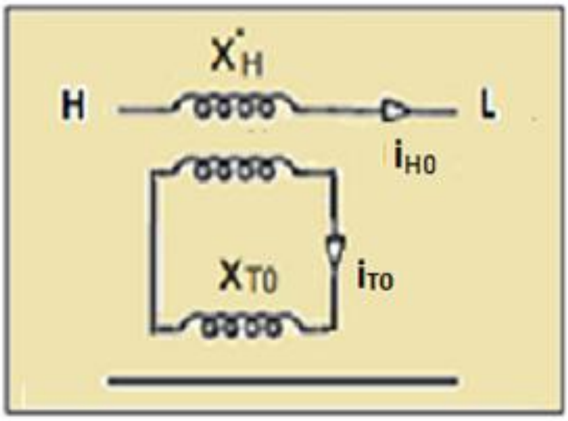

Fig. 6 Zero-sequence equivalent circuit of autotransformer with neutral isolated from ground

The tertiary winding provides the required magneto-motive force, as per Ampere's Law for the ampere-turn equilibrium. Hence, as stated, for this condition the common winding ceases to be a conductive path of the zero-sequence current; hence, the unit becomes a two-winding transformer, as shown in Fig. 6, with a 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 autotransformer zero-sequence reactance; this parameter actually changes from the original X_{HL} to a new value X'_{HL} equal to $X'_{HT.}$ Comparing the Figures 3 and 4 with 5 and 6, plus the fact that the associated magnetic circuit, for most construction types, remains basically the same; while the windings turns 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 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 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, with unbalance considerations delimited differently). As a matter of fact, such a grounding ratio, in most applications and depending on equipment nameplate values, it thus can be inferred it will undergo only a relatively minor change after surge-arrester GIC blocking device deployment; this becomes a fundamental attribute of this mitigation concept.

Numerical Example

A numerical example is worked out, as detailed in Appendix A, with a full computation of the grounding coefficient before and after the deployment of the neutral arrester device, as it applies to protect a typical grid three-winding autotransformer from the circulation of GIC. Calculations associated to both Fig. 3/4 and Fig. 5/6 equivalent circuits are carried out. Results indicate that for the steady-state solid ground condition the computation yields the anticipated value of 1.0; furthermore, upon deployment of the neutral arrester device (Fig. 5/6) the calculation of the grounding coefficient yields a value of 0.85; which represents only a small reduction, to some extent unanticipated by the common perspective. Sensitivity analyses done showed that this grounding coefficient could also increase somewhat depending on transformer nameplate values; however staying between the solid and effectively-grounding range.

GSU Transformer

Differently to the autotransformer case, this is a two-winding transformer, typically with a large turns ratio, as generator voltage ratings are considerably lower than the corresponding transmission ones. Its symmetrical-component equivalent circuits are shown in Fig. 7 and Fig. 8, respectively. Furthermore,

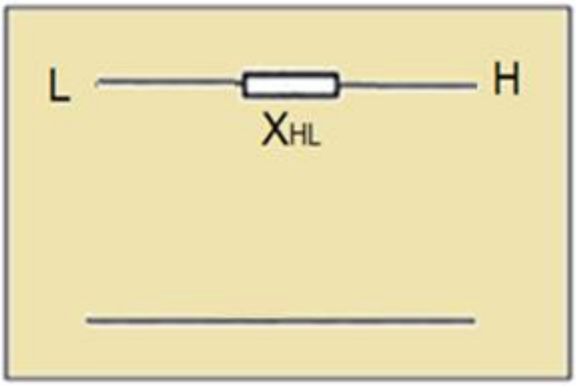

Fig. 7 GSU transformer positive or negative sequence per-unit equivalent circuit

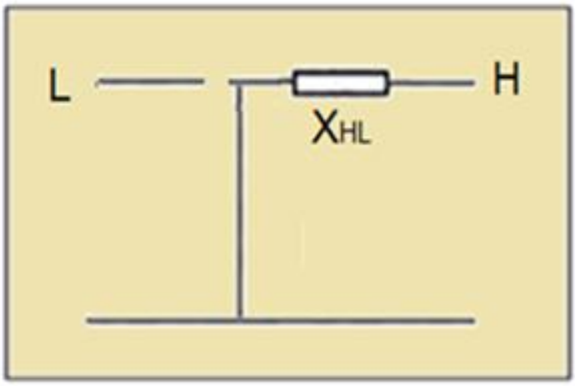

Fig. 8 GSU transformer zero-sequence per-unit equivalent circuit

it is important to preliminary assess the nature and impact of ground residual currents in this case. First of all, no 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 [7], moreover it can be said that no significant flow is possible through the transformer when and if an arrester device has to be deployed, given the unit arrangement substantial zero-sequence impedance and hence, any neutral shift would be limited to a Ferranti rise in the zero-sequence network; rise 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 wiould basically see no real duty from the unbalance examination.

Modelling of the GIC-Blocking Arrester Device

Based on 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 namely, the steady-state and the ground-fault ones.

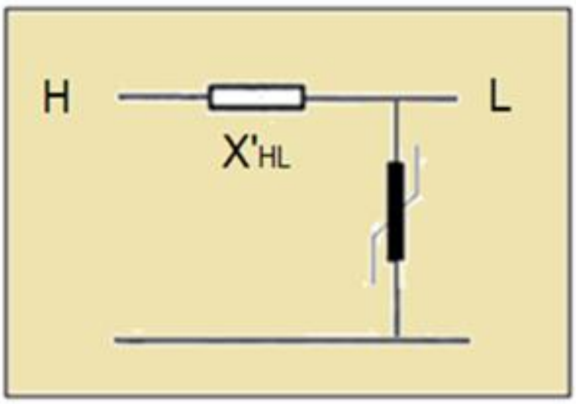

Fig. 9 Zero-sequence equivalent circuit of Autotransformer under surge-arrester device deployment

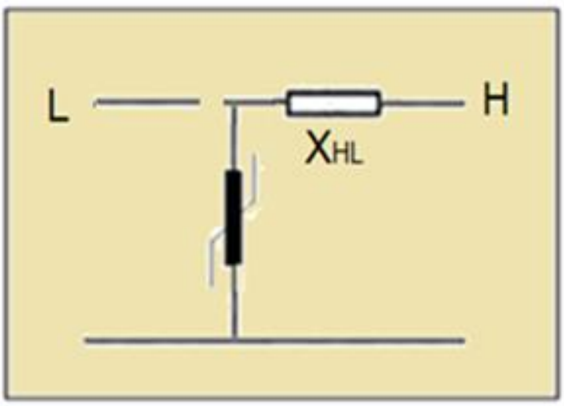

Fig. 10 Zero-sequence equivalent circuit of GSU transformer under surge-arrester device deployment

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 transformer equivalent circuits. Contrariwise, the zero-sequence circuit must include the specifics of the neutral-grounding device and winding connections. In that sense, the equivalent circuits after arrester deployment assuming no faults, for the two typical transformer types considered. Fig. 9 shows the zero-sequence equivalent circuit for the grid autotransformer, while Fig.10 shows the zero-sequence equivalent circuit for a GSU unit. In the former case, it can be pointed out that the neutral-grounding surge-arrester device is in a shunt connection with respect to the prevailing High-to-Low transformer reactance whereas, in the GSU case, the unit short-circuit reactance is in series with the arrester device. For the steady-state unfaulted case, the arrester device basically is an open circuit causing the autotransformer zero-sequence circuit to remain fairly unchanged from the device pre-deployment state. Moreover, the arrester device, not traversed by the zero-sequence current, is mostly impervious to it or to its attendant caused voltage drop, for typical grid conditions and arrester ratings. In the GSU case, the arrester device open-circuit level renders the transformer temporarily ungrounded. However, as pointed out above, the potential zero-sequence Ferranti-rise effect on the arrester is unlikely to trickle down any energy duty for typical grid conditions and arrester ratings.

Device SLGF Response

The SLGF response is again different for both apparatus construction types selected. As far as the autotransformer is concerned, the fault current is shown not to traverse the arrester device; its voltage gets essentially determined by the low-side downstream voltage drop to the fault point; should that magnitude exceed the device protective level, it might turn it into an activation; this, rarely 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 for the very short time of temporary 'ungrounded' conditions); a voltage-zeroing wave surge follows, propagating towards the transformer neutral; for 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 [8], sustain continuously the protective level as the surge settles at the steady state value. Fig. 11 illustrates the time sequence from the initial arcing ground to the actual SLGF. This also comprises an added neutral-grounding surge-arrester device functionality, setting that fault. In addition, cited extensive research asserts that, given the energy surge arrester must dissipate, it will conceivably turn into a safe valve-relief mode, developing a contouring external arc; this event causing besides the need for such an arrester to be replaced ex-post. This feature is common to all blocking devices which include neutral-grounding arresters, besides having a successful testing record. Additionally, surge arresters must comply with IEEE Short-circuit Test guidelines, calling for a large safety margin on this application. Moreover, the computation of the external arc resistance yields values indicating neutral voltages to be negligible under SLGF currents [9].

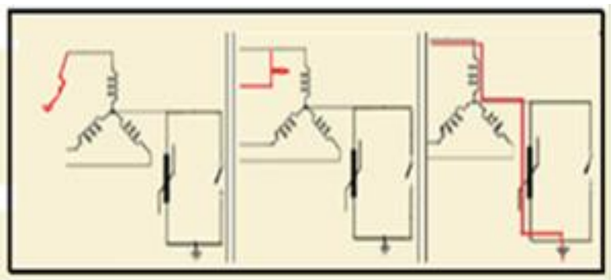

Fig. 11 SLGF sequence of events for a GSU Transformer

Substation Placing of a GIC-Blocking Surge Arrester

The substation design considerations for arrester-apparatus separation is well established for typical overvoltage protection; in general it is based on an impulse-wave surge which constrains a physical proximity to the protected equipment. Notwithstanding, this is not the case for the GIC neutral-blocking application; contrariwise here, it is associated to a much slower SLGF voltage oscillation at the transformer neutral level. Consequently, the proximity constraint can be conveniently relaxed, with the arrester placed at an optimal design distance. This abundance of precaution would make, even for an unlikely class IEEE-tested arrester valve-relief aftermath, totally inconsequential to the integrity of the transformer.

Conclusions

This paper has presented basic design tools for the implementation of the GIC surge-arrester mitigation device. In this regard, this unit, typically used for protection of power apparatus and as a component associated to a number of known GMD countermeasures, has been proposed as the sole element committed to suppress the undesired GIC flow through transformers. Indeed, an added function to the surge arrester is revealed and presented whereby, it will not only prove adequate in yielding apparatus neutral insulation protection but also provides an essential GIC blocking ability. Additionally, this paper has discussed equivalent circuit diagrams showing the basic arrangement of the scheme introduced. Such an outline comprising additionally a transformer neutral-grounding switch, combination in turn capable of a timely switching criteria (outside the scope of the paper); nonetheless, the assembly layout gives a notion of simplicity and minimum substation redesign impact. Furthermore, following cited independent research regarding the surge arrester suitability as a useful protective component of GIC mitigation schemes; they have also confirmed a reliable transformer neutral insulation protection when that device is deployed. Moreover, the proposed technology entirely relieves the need for the consideration of major blocking components, thus the presented concept allows for a footprint reduction which could prove critical minding the space restrictions at transmission/generation substations. It can be concluded that, either from a steady-state, ground-current residuals, SLG faults, parametrical invariance or GIC-blocking perspectives, the standalone arrester device compares favorably with the ones alternatively based on a condenser or resistor, yet without any of their potential inherent risks. The difference can only be found at the blocking-function means: one performed by a capacitor/resistor 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 only a fraction of an autotransformer's GIC, hence again, the question of incremental cost/benefit associated to the alternative use of sizable installations remains quite compelling; in addition, these units are called to operate infrequently. Also the introduced protective approach could help minimizing GMD-driven operational procedures.

To Probe Further

Further research is required to study the grid circuit-breaker challenges stemming from the expected substantially higher EMP-E3 GIC, impeding current interruption due to the most likely prevailing non-zero crossing of the resulting wave. This could put transformers at risk, even for a limited time this conditions could last; problem worsened by the combination of current overload and harmonic distortion, causing a relatively unknown thermal/mechanical impact. Moreover, addressing this issue, an across-the-board technical documentation templet must be reviewed in order to assist attaining a site-specific implementation of the presented cost-effective GIC blocking scheme. As anticipated above, ultra-fast sensing and switching assets have become essential in order to cope with EMP shocks effectively; these features become key to avoid a dependence on alternative immature technologies, 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 cost-effective innovative concepts, as the one presented, is highly recommended.

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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 x 5 = 0.85 pu on 500 KV/500 MVA base
X_{LT} = 0.13 x 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
$X_L = 0.5(X_{HL}+ X_{LT} - X_{HT}) = 0.5(0.10 + 0.75-0.85)$ $X_L = 0.00$ 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 turns-ratio correction factor becomes:

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

And the prevailing zero-sequence High-to-Low reactance can be computed as:

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

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

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

hence:

$X'_{HL(zero\ sequence)}/X_{HL(positive\ sequence)} = 0.85$