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Effects of GIC Neutral Blocking Devices (NBDs) on Transmission Lines Protection Performance and Potential for Resonance

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SUMMARY

Geomagnetic Induced Current (GIC) is a quasi-dc current that flows in grounded power systems due to the variations of the earth surface potential caused by geomagnetic storms. GIC is reported to cause half-cycle saturation in power transformers which will result in: a drastic increase in the reactive power consumption of the transformer, transformer heating, harmonics and potential misoperation of protective relays. Several GIC blocking devices (NBDs) have been proposed, all with the idea of implementing a capacitive impedance in the neutral of power transformers in order to block the flow of the GIC into the system. Concerns have arisen over the performance of line protection relays while these NBDs are in service especially when zero sequence polarizing is used, and additionally over the energy handling of the metal oxide varistor (MOV) protected type of NBDs. The need to avoid resonance was cited as a design guide. Meanwhile, most of the published work has been related to small scale, or partial systems.

In this study real-time simulation with actual hardware-in-the-loop (HIL) testing is utilized to investigate the impact of NBD on the performance of line protection relays. The system used in this study is the IEEE-39 bus system. This study has shown that the distance protection relays will not be affected by the insertion of the NBDs, however when a fault occurs the energy through NBDs' MOV was found to be excessive.

In addition, the potential for resonance (in both steady state and during ground fault conditions) between the neutral capacitor and the system was investigated. The results shows that there is a possibility for resonance under steady state unbalance, however in some cases actual resonance may be masked by a high damping system so that it becomes indiscernible. Under fault conditions, results indicate that even for non-resonating system conditions care is needed to avoid catastrophic damages by providing a backup spark gap for MOV devices.

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KEYWORDS

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GIC, HIL, Hypersim, IEEE-39 bus, MOV, NBD, Protective Relays, Real Time Simulation, Resonance under Fault Conditions, Steady State Resonance.

INTRODUCTION

Geomagnetic effects on electrical networks caused by geomagnetic storms have been recognized and studied since the last century, and a number of reports and papers have since been published in the mainstream power systems literature. EPRI produced reports aiming at providing tools for estimating the effects and mitigating the problems caused by geomagnetically induced current in the early 1980's [1,2]. It was however the 1989 geomagnetic disturbance causing the Hydro-Quebec blackout that prompted the North American Electric Reliability Corporation (NERC) to take action and call for improved geomagnetic storm forecasting [3]. The incident also led to renewed interest in geomagnetic mitigation measures and the early 1990's saw emergence of methods describing the implementation of neutral blocking/bypass devices in the high voltage side of power transformers [4,5]. These methods focused mainly on the optimum sizing of the blocking capacitors and viable technical solutions for bypassing the capacitors in the event of a fault involving the high voltage grounding loop. Capacitors were sized with a view to minimizing the crest voltage caused by both the ac steady-state zero sequence voltage persisting in the ground system, and the dc voltage due to geomagnetic effects in addition to HVDC galvanic coupling, if existing. Provisions for making the capacitor impedance small enough to avoid resonance with zero sequence system impedances were introduced in the optimizing equations [5]. Bypassing the capacitors during fault conditions proved a dilemma; while spark gaps would be able to handle the energy sustained through them under fault conditions until a slower mechanical shunt switch successfully closes, the variability of flash-over characteristics makes the viability of the scheme doubtful. On the other hand, metal-oxide varistors (MOVs) have well defined break-down characteristics but suffer from poor energy handling. In order to adequately protect the capacitors from over-voltages under fault conditions and be able at the same time to safely convey the sustained fault energy through them, researchers have put forward solutions involving either a large number of MOV's or some form of low voltage triggered spark-gaps [2,5].

It is not the objective of this study to explore the technical alternatives for designing geomagnetic blocking devices (NBDs). Rather the idea is to investigate two different benchmark-type NBDs as used by EPRI [6], to assess the effect on (a) relaying performance under severe ground faults and (b) resonance performance in steady state as well as under fault conditions and (c) energy handling capabilities under the fault conditions prevailing in (a). Furthermore the study aims to impose these conditions on a sufficiently larger and more complex system than the smaller scale or partial systems examined in some of the publications referenced in this paper. This is the slightly modified IEEE-39 system, comprising 10 generators, 12 transformers and 34 transmission lines. The number of NBDs involved in the study is 12, located at the neutrals of the high voltage side of each transformer. The original IEEE-39 bus system has a 345 kV high voltage system, but this was changed here to 500 kV to comply with the benchmark GBD requirements, while retaining the original system topology. The 500 kV line data was changed accordingly using typical data.

A unique feature of this study is that it was conducted in real-time with actual hardware-in-the-loop testing comprising actual SEL-411L distance relays responding to the fault conditions. The relays facing each other at opposite ends of the line are interfaced through a Directional Comparison Blocking (DCB) scheme implemented through the IEC 61850 protocol. The following section provides a brief overview of the HIL testing scheme along with a description of the system model and its simulation in real-time using Hypersim Real-Time Digital Simulator (RTDS). Section III describes the methodology followed in this work to test the protection performance, resonance potential, and the energy handling capabilities of the MOVs. Sections IV and V presents the investigation results along with all the findings, recommendations and conclusions of this work.

System Description and Modelling in Real Time

A. General Description of the IEEE-39 Bus System

Fig. 1 shows the New England 39 bus system which consists of 10 generators, 34 transmission lines, 12 transformers and 18 load buses. The transmission voltage level for the original New England 39-bus system is 345kV. For this study the voltage of the transmission system was upgraded to 500kV while maintaining the original topology of the system. In addition, GIC blocking devices (NBDs) are installed in all transformers' neutrals.

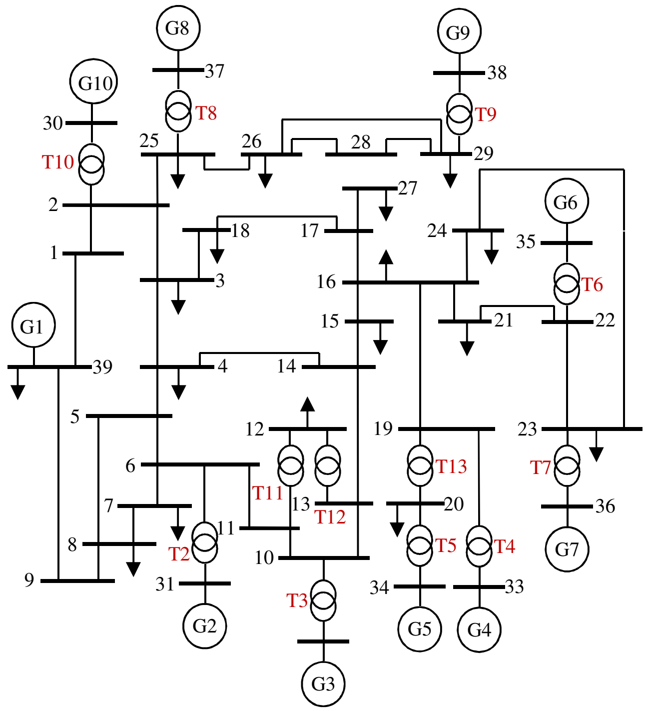
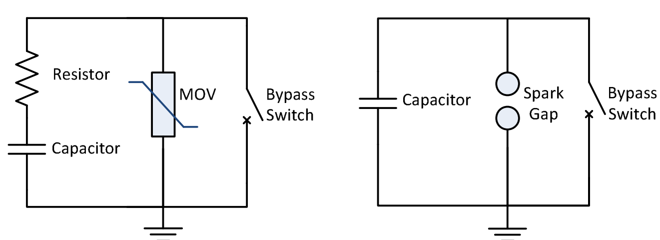


Fig. 1. IEEE-39 Bus System

B. GIC Blocking Device

Fig. 2 shows the two designs of NBD that are used in this work. The first uses a 5600MVar, 2.4kV, 1.03 ohms capacitor in series with a 1 ohm resistor. Protection against severe fault currents is provided using a 4.0kV, 33.32kJ MOV. The second design uses a 1200MVar, 7.2kV, 43.2 ohms capacitor which is protected using a 14kVrms, 20 kV crest spark gap.



a) NBD Design I *b) NBD Design II*

Fig. 2. GIC Blocking Devices

C. Hardware in the Loop testing

Hardware in the Loop (HIL) simulation is a technique that can be used to perform system-level testing for different control and protection schemes in a very comprehensive and cost-effective manner. In this technique a Real Time Digital Simulator (RTDS) is used to simulate the power system in real time while different protection relays and controllers are connected to the simulator's Input/outputs ports. This provides a realistic environment for testing the functionality and performance of these devices as well as the system response to their actions.

D. Real-Time Digital Simulator (RTDS)

The RTDS used in this project contains a powerful real-time target computer equipped with up to twelve 3.3-GHz processor cores. The digital simulator consists of an upper section that contains analog and digital I/O signal modules and a bottom section which contains the multi-core processor computer that runs the real-time software. The software interface allows the user to create customized models using basic control blocks or models designed in the MATLAB/Simulink environment. A key feature in the software is that it allows complete control and monitoring of the model while running in real time.

E. Amplifier

The real-time simulator generates a maximum of 16V in the analog output port, and the relay nominal voltage is rated at 66.39 V line to ground voltage so an amplifier is required to amplify the voltage signals to the relay voltage levels. The amplifiers have the capability of amplifying both low level voltage and current signals, using different and multiple amplification ratios. These amplifiers have up to six output voltage channels and six output current channels

F. Relays

Two distance relays are configured to be connected across a selected 500 kV line. These relays are configured in a Directional Comparison Blocking (DCB) scheme where the communication is performed using the IEC61850 protocol.

Methodology

A. HIL Testing and Assessing of Transmission Lines Protection

In this work hardware-in-the-loop (HIL) testing technique is used to evaluate the performance of transmission lines protection relays while the NBDs installed in the neutral of transformers are in service. The system used in this study is the IEEE-39 bus system shown in Fig. 1. This system was built successfully in Hypersim real time digital simulator platform. Single phase-to-ground faults are applied at various locations in the system. For each fault scenario, secondary quantities (voltages, currents) generated from the digital simulator are applied to SEL-411L relays via a power amplifier. The relays' trip signals are then fed back to the simulator via its digital input port. These signals are used to operate two breakers; one at each end of the protected line. Fig.3 shows the data flow for HIL testing scheme.

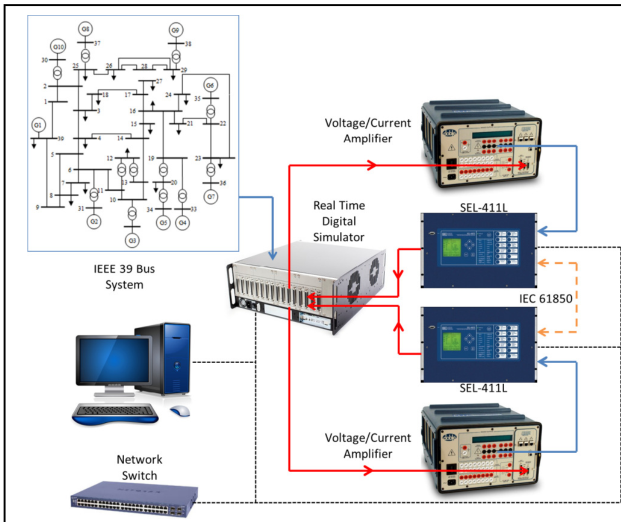


Fig. 3. HIL Data Flow

B. Resonance Analysis

The second objective is to investigate steady-state resonance and possibility of resonance under fault conditions. Under steady-state conditions the occurrence of resonance in the system zero sequence network should be expected to result in an amplification of neutral current and voltage across the blocking device. If damping is insufficient in the zero sequence network then the voltage developed across the blocking device could be greater than the device rating especially when combined with DC voltage caused by a geomagnetic disturbance. This would operate the protection for the device (either by MOVs or gap spark-over) and the NBD would need to be bypassed and removed from service. Also, under fault conditions, the occurrence of resonance in the system would result in severe over voltages across the NBD upon a fail-open of the MOV from a previous fault.

The methodology implemented here to search for resonance is as follows: Since the system is complex, it is not a trivial matter to construct the zero sequence network at any bus from the circuit viewpoint (The steady state zero sequence network is somewhat different from that used in fault analysis, in addition to the presence of loading). A practical method is, after inserting all capacitor blocking devices in place, to open the terminals of one of these devices, at the point where resonance is to be investigated. In the case where steady state resonance is investigated, the system is unbalanced by manipulating the nearby loads to create about 1.2% zero sequence steady-state voltage at the open neutral voltage with reference to the system ground (the voltage between the open neutral and ground is identically equal to the zero sequence voltage E_0). Reference [5] reports that 1.2% of zero sequence voltage was measured on the Radisson/LG2 system, although in lower voltage systems it may be as high as 2% [7]. For the other case where resonance under fault conditions is investigated, an A-G fault is applied on the immediate bus to create the needed unbalance.

Next, the neutral point is grounded with the NBD device removed, and the simulation is allowed to stabilize to measure the neutral ($3I_0$) current at that point. The resulting Thévenin's complex zero sequence impedance is then given as

$$\frac{\overline{Z}_0}{3} = \frac{\overline{E}_0}{3\overline{I}_0} \qquad (1)$$

The imaginary part of Z_0 is examined to see if it tunes to $3X_c$ since the conditions for resonance are:

$$\text{IMG}\{\,\overline{Z}_0\,\} = 3X_c \qquad (2)$$

The NBD capacitor is then inserted into the network to simulate its actual resonance performance, with the expectation that resonant conditions should result in the highest voltage across it.
After the insertion of the capacitor the neutral current will be:

$$3\overline{I}_0 = \frac{3\overline{E}_0}{\overline{Z}_0 - 3jX_c} \approx \frac{3\overline{E}_0}{R_0} \qquad (3)$$

And the neutral voltage will be:

$$\overline{V}_n = \overline{I}_0 \times 3jX_c \qquad (4)$$

As it turns out, resonance does not necessarily result in the most adverse voltage conditions. It may be possible in some cases that the resonance is sufficiently damped by the resistive part of Z_0 such that the currents and overvoltage are not destructively high, whereas another case may arise where the overall impedance $Z_0 - 3jXc$ is low, although not necessarily in resonance, and such that the resulting large steady-state neutral current leads to unacceptable overvoltages across the NBD.

C. MOV Energy Handling Assessment

It is necessary to pay attention to the energy handling capabilities of the MOVs used to protect the NBD capacitor. If the MOV energy limit is exceeded, it will fail open leaving the capacitor with no high voltage protection in the absence of a backup spark gap. Failed MOV conditions may result in a very high voltage across the capacitor, a condition which may cause the capacitor to fail, or even fail the transformer insulation.

To investigate energy handling, faults are applied at various points in the system while the energy through the MOVs is monitored. Since the typical clearing time for a fault on the 500 kV is 3-4 cycles, all faults in this study are set to clear in 4 cycles. The MOV protecting the capacitor is required to successfully sustain the fault energy throughout the fault duration. Otherwise, it will be considered as failed-open. The fail-open mode is selected here, since this is the failure that will result in overvoltages.

Results

A. Results of HIL Testing and Assessing of Transmission Lines Protection

As the IEEE-39 bus system is fairly large, only three lines were selected to examine the relaying performance. These lines were chosen because they are connected to transformers at one or both ends.

The real-time digital simulator produces voltages and currents signals for the buses at the terminals of the selected lines. These signals are amplified and injected into two SEL-411L relays which are used to protect a 500KV line. Trip signals generated by the relays are fed back into the simulator and used to trip the simulated line. A DCB scheme is applied to the 500KV line were the communication between the relays is achieved using IEC61850. Both relays are given IP addresses and connected to an Ethernet switch that allows passing of the GOOSE messages.

Before connecting the NBDs in the transformers' neutrals, in and out of zone faults were applied on the selected line to ensure that the DCB scheme is working correctly and selectively.

Then Type-I NBD (1.03 ohm) was connected in all transformer neutrals and A-to-G faults were applied in three different lines. These faults were placed close to the buses (a total of 6 buses) to simulate the highest current through the NBDs. During these tests, all SEL-411L were configured at first to use negative sequence measurements as polarizing quantities.

In this paper, results from line 22-23 only on the IEEE-39 bus system are presented as the results from the other simulations are similar. For an A-G fault on bus 22 with the relays configured to use negative sequence polarizing, voltage and current waveforms on bus 22 are shown in Fig. 4 and Fig. 6 respectively, while voltage and current waveforms on bus 23 are shown in Fig. 5 and Fig. 7 respectively. COMTRADE files for the fault were measured from the relays at both ends. Fig. 8 shows a screenshot of the COMTRADE file for the relay at bus 22 were the Z1G , Z2G, 32GF and 3PT are shown. Fig. 9 shows the COMTRADE file for the relay at bus 23. It can be seen that the COMTRADE files shown in Fig. 8 and Fig. 9 are identical to the simulated waveform shown Fig. 4, Fig. 5, Fig. 6 and Fig. 7.

It can be seen from the COMTRADE file at bus 22 that the fault was cleared in a little more than 4 cycles. This is because although the timer Z1GT was set to 4 cycles to account for breaker time since the trip signal from the relay is fed directly to the simulator, additional time is required for the fault detection and for the relay contacts to close. Similarly, the relay at bus 23 tripped in about the same time. In other words, both relays have tripped correctly. In addition, both relays detected the fault location with acceptable range. The relay at bus 22 detected the fault at 0 km, while the relay at bus 23 detected the fault at 31.87 km (a 3.4% error).

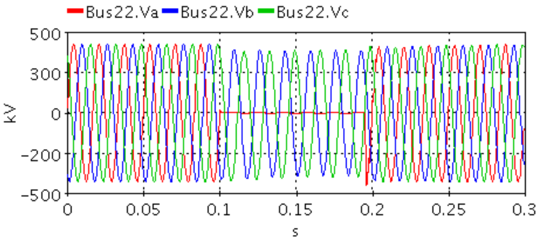


Fig. 4. Simulated voltages at bus 22

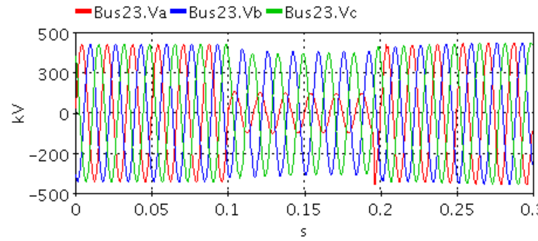


Fig. 5. Simulated voltages at bus 23

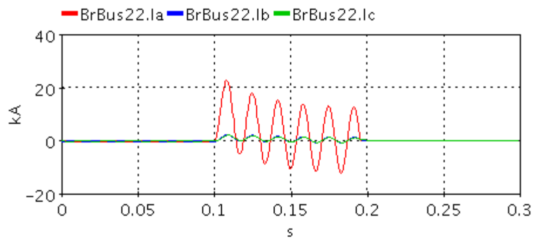


Fig. 6. Simulated currents at bus 22

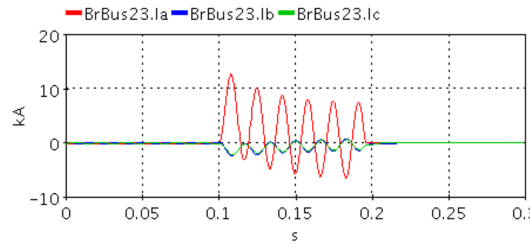


Fig. 7. Simulated currents at bus 23

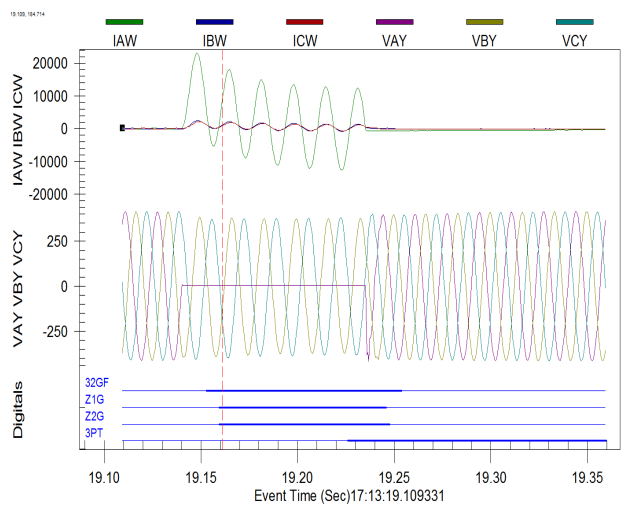


Fig. 8. Relay's event file at bus 22 (COMTRADE)

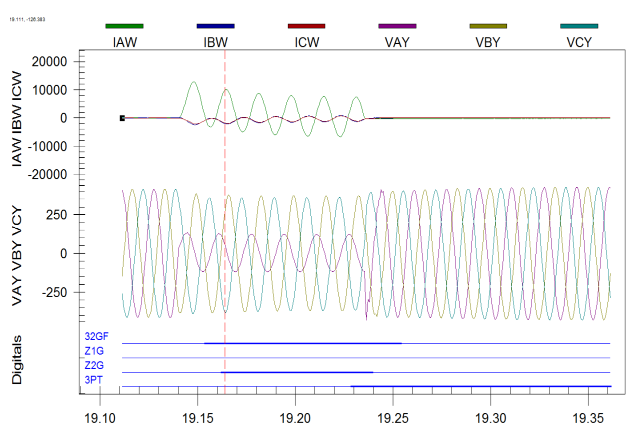


Fig. 9. Relay's event file at bus 23 (COMTRADE)

Then the polarizing quantity was changed to zero sequence current and the two SEL-411L relays were then configured to use zero sequence polarizing obtained from the closest transformer's neutral. The previous A-G faults were repeated to examine this configuration. Voltages and currents at the faulted bus and the remote bus are identical to the previous fault. Fig. 10 shows a screenshot of the COMTRADE file for the relay at bus 22 were the Z1G , Z2G, 32GF and 3PT are presented . Fig. 11 shows the COMTRADE file for the relay at bus 23. These COMTRADE files illustrate a tripping time of a little more than 4 cycles at both buses due to the aforementioned reasons. Hence it could be concluded that whether negative sequence or zero sequence quantities are used as polarizing quantities, the SEL-411L relays were always able to detect the fault and its location correctly and therefore trip properly.

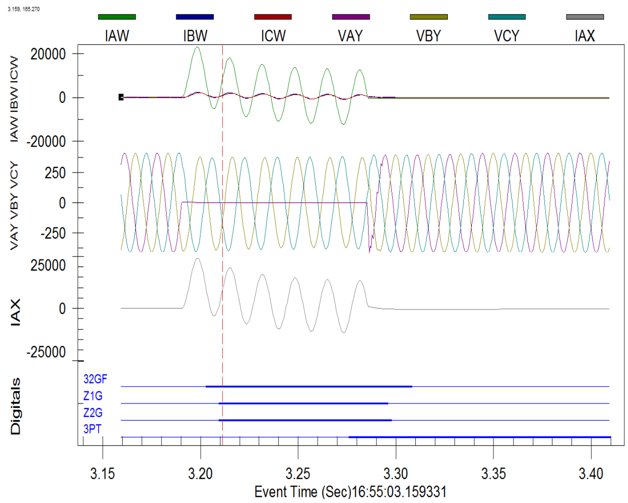


Fig. 10. Relay's event file at bus 22 (COMTRADE)

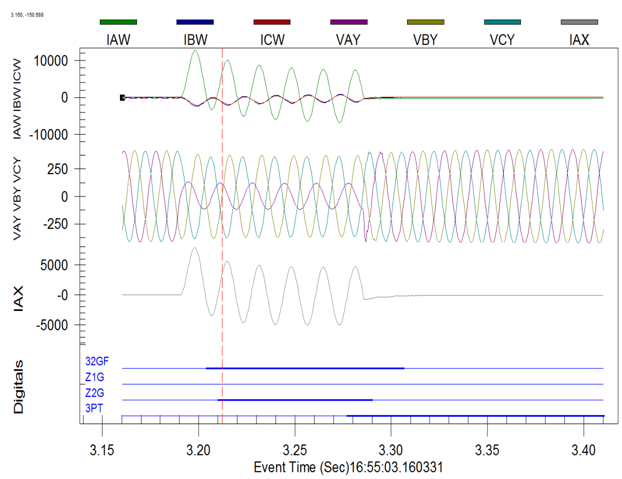


Fig. 11. Relay's event file at bus 23 (COMTRADE)

The same fault was repeated again for the Type-II (43.2 ohm) NBD. Voltage and current waveforms on bus 22 are shown in Fig. 12 and Fig. 14 respectively, while voltage and current waveforms on bus 23 are shown in Fig. 13 and Fig. 15 respectively. COMTRADE files for the fault were pulled from the relays at both ends. Fig. 16 and Fig. 17 show screenshots of the COMTRADE files for the relay at bus 22 and bus 23 when negative sequence polarizing is used. Both relays operated correctly and selectively.

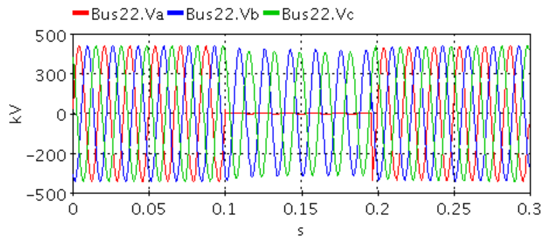


Fig. 12. Simulated voltages at bus 22

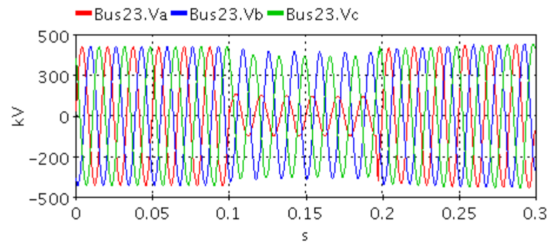


Fig. 13. Simulated voltages at bus 23

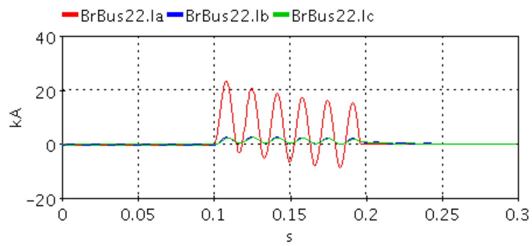


Fig. 14. Simulated currents at bus 22

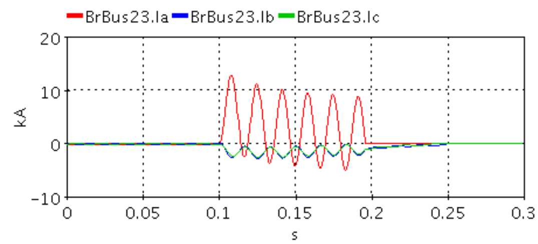


Fig. 15. Simulated currents at bus 23

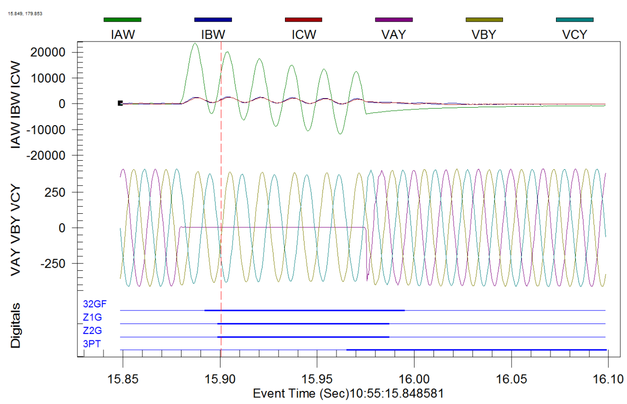


Fig. 16. Relay's event file at bus 22 (COMTRADE)

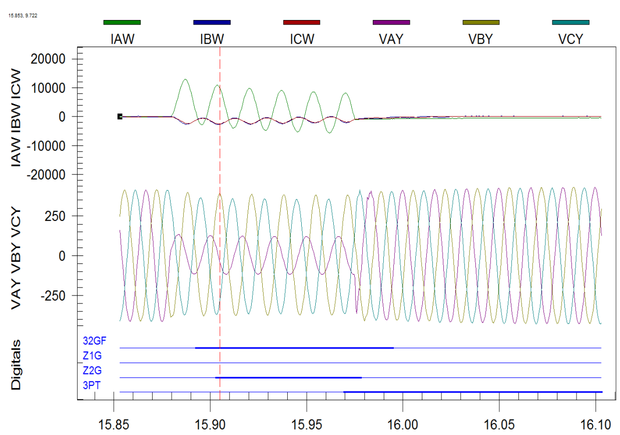


Fig. 17. Relay's event file at bus 23 (COMTRADE)

Also, The two SEL-411L relays were then configured to use zero sequence polarizing obtained from the closest transformer's neutral. The previous fault was repeated to examine this configuration. Voltages and currents at the faulted bus and the remote bus are identical to the previous fault. COMTRADE files for the fault were pulled from the relays at both ends. Fig.18 and fig.19 show screenshots of the COMTRADE files for the relay at bus 22 and bus 23 respectively. It can be seen that both relays worked properly.

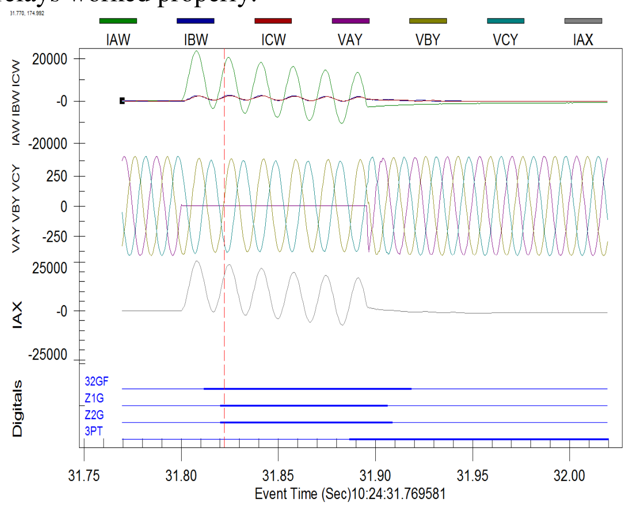


Fig. 18. Relay's event file at bus 22 (COMTRADE)

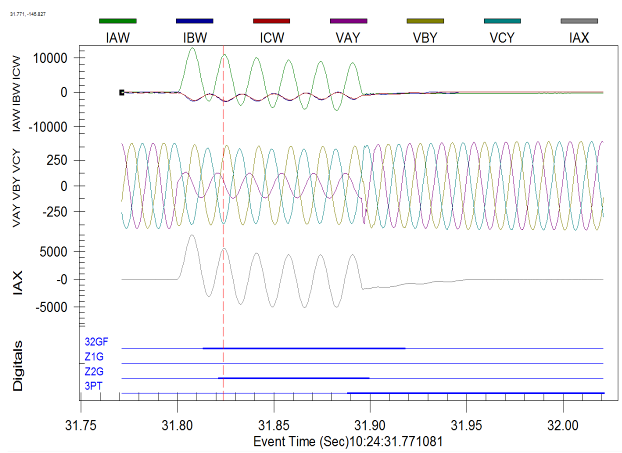


Fig. 19. Relay's event file at bus 23 (COMTRADE)

B. Results for Resonance

1) Steady-State Resonance

The results of steady state resonance analysis for the two NBD capacitive impedance values of 1.03 ohms and 42.3 ohms are summarized in Tables 1 and 2.

TABLE 1
THÉVENIN'S ZERO SEQUENCE IMPEDANCE (OHMS) FOR THE 1.03 OHM NBDS

	Resistance (ohm)	Inductance (ohm)	$\frac{V_n}{E_0}\%$
T2	3.63	17.06	8.6
T3	1.82	14.80	10.2
T4	1.64	17.03	8.9
T5	1.31	4.58	33.9
T6	4.87	21.09	6.9
T7	4.99	21.59	6.7
T8	4.77	20.67	7.0
T9	34.02	52.39	2.3
T10	3.95	18.57	7.9
T11	1.64	18.73	8.0
T12	2.81	19.98	7.4
T13	3.63	17.06	8.6

TABLE 2
THÉVENIN'S ZERO SEQUENCE IMPEDANCE (OHMS) FOR THE 42.3 OHM NBDS

	Resistance (ohm)	Inductance (ohm)	$\frac{V_n}{E_0}\%$
T2	5.60	6.00	114.8
T3	11.81	-3.39	89.9
T4	58.07	11.29	65.2
T5	1.24	4.61	111.8
T6	33.11	24.95	114.3
T7	33.80	25.38	113.1
T8	19.62	27.51	171.9
T9	35.06	38.93	122.3
T10	18.71	23.94	160.9
T11	11.69	1.64	100.0
T12	10.10	5.83	111.6
T13	5.60	6.00	114.8

The last column in Tables 1 and 2 is interesting. It shows the ratio of closed circuit neutral voltage V_n (with NBD in service) to open circuit voltage E_0. The open circuit voltage was, as mentioned, set to 1.2% of system voltage, which on a 500 kV level would be around 3.46 kV. The 1.03 NBD has a voltage rating of 2.4 kV for the capacitors and a MOV V_{mcov} rating of 3.4 kV. Clearly there is no issue regarding over-voltages for this type of NBD while in service, as Table 1 reveals. Additionally there seems to be no potential for resonance, with the closest inductive impedance to the 1.03 ohm capacitive impedance being 4.58 ohms seen at the neutral of transformer T_5. The closed circuit voltage across the device at this point, though the highest among the others, only goes to about 34% of the open circuit voltage.

Table 2 however, for the 42.3 ohm NBD reveals a different performance. The capacitors have a 7.2 kV rating and the spark gap is set to break at between 16 and 24 kV. Almost all the cases show voltage amplification across the NBD after closing the neutral, with the worst being 172% or about 5.95 kV. This is still under the capacitor tolerance, but by no means a case free of concern. It is interesting to note that the point closest to resonance - at the neutral of transformer T9 - does not suffer the highest voltage amplification upon closing the neutral and only goes up to 122%. The reason is that this condition, in particular, has a high resistive damping. It should not be inferred therefore, that resonance conditions alone are responsible for over-voltages. Rather a number of factors in addition to resonance, such as system resistive loop seen at the point of interest, should be taken into account.

2) Resonance under Fault Conditions

The reason for including an investigation for possible resonance under faulted conditions, although the MOVs and spark gaps are expected to operate for these conditions, is to determine whether the situation could be aggravated by resonance. Failure of the MOVs, in particular, an issue discussed in [6] due to high fault energy, was a concern and some proposed designs do not include a backup spark-gap in case the MOV fails open [5]. To have a resonant loop where the MOV has failed open on a previous fault and has exposed the capacitor with no spark-gap bypass could be truly catastrophic.

The system's Thévenin's zero sequence impedances at different locations under fault conditions for the two NBD capacitive impedance values of 1.03 ohms and 42.3 ohms are summarized in Tables 3 and 4. The last column again shows

TABLE 3
THÉVENIN'S ZERO SEQUENCE IMPEDANCE (OHMS) FOR THE 1.03 OHM NBDS

	Resistance (ohm)	Inductance (ohm)	$\frac{V_n}{E_0}\%$
T2	1.96	11.14	13.4
T3	1.04	9.87	15.5
T4	0.36	10.20	15.2
T5	0.53	2.28	71.1
T6	1.66	13.55	11.0
T7	2.48	12.73	11.6
T8	2.26	12.80	11.6
T9	7.12	21.91	6.3
T10	1.72	10.85	13.9
T11	1.23	11.69	13.0
T12	1.28	12.17	12.4
T13	0.50	9.54	16.3

TABLE 4
THÉVENIN'S ZERO SEQUENCE IMPEDANCE (OHMS) FOR THE 42.3 OHM NBDS

	Resistance (ohm)	Inductance (ohm)	$\frac{V_n}{E_0}\%$
T2	6.14	7.31	119
T3	17.15	11.57	120
T4	8.30	18.63	167
T5	0.49	2.31	106
T6	7.36	17.33	161
T7	17.30	15.57	133
T8	8.89	13.69	140
T9	8.33	20.63	180

T10	4.64	13.46	144
T11	17.30	15.57	133
T12	12.63	13.54	134
T13	7.51	21.82	191

the ratio of closed circuit neutral voltage V_n (with NBD in service) to open circuit voltage E_0. The MOVs and spark gaps have been removed as they would break down and inhibit resonance/overvoltage conditions. The open circuit voltages E_0 are extremely high, most in the 200 – 250 kV window for the 500 kV system, and are certainly above the typical neutral BIL of around 110 kV.

The tables do not show a serious proximity to resonance for either type of NBD, but in both cases the closest Thévenin impedance to that of the NBD capacitor results in the largest over-voltage. For the 1.03 ohm NBD this was at T5 with an overvoltage of 71% of open circuit value, while for the 43.2 NBD an overvoltage of 191% appeared across the device at T13.

This analysis confirms that under all fault conditions it becomes imperative to effectively ground the system through MOV or spark gap devices. A further requirement is that in case the MOV is incapable of handling the fault energy and fails to open-circuit conditions, a backup spark-gap becomes mandatory.

C. Energy handling

In order to assess the energy handling capabilities of the MOV, three different faults were applied and the energy through the MOVs was measured. Any MOV that passes more than 33.32 KJ is considered failed open [6]. The faults are as follows:

1- A-G fault at bus 18, cleared in four cycles. During this fault, only the MOV at T10 neutral has failed. The energy through it was 92.4 KJ.
2- A-G fault at bus 25, cleared in four cycles. Two MOVs have failed one at T10 after passing 391 KJ and the other is at T8 after passing 2.86 MJ.
3- A-G fault at bus 17, cleared in four cycles. After 13 ms of placing the fault the MOV at T10 has failed due to passing an excessive energy of 37.6KJ. After another 17 ms, MOVs at T4, T6, and T7 have failed simultaneously. These MOVs have passed 39.77KJ, 74.56KJ, and 64.2 KJ respectively. 15 ms after that, also T8 and T3_3 MOVs have failed after passing 43.65 KJ and 34.83 KJ respectively.

These three scenarios indicate that detailed energy handling calculations need to be done before inserting any NBDs. This is to ensure that the MOV does not fail at the next fault incident. The most severe energy will pass through an MOV when the fault is at the immediate bus. For example, an A-G fault which was placed at bus 22 caused energy of 6 MJ to pass through T6 MOV and the NBDs energy limit was exceeded in only 2 milliseconds. Fig.20 shows the energy for T6 MOV.

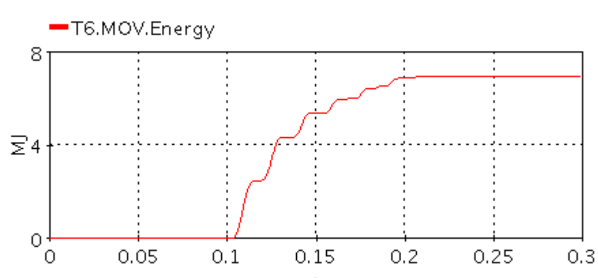


Fig. 20. Energy through T6 MOV

CONCLUSIONS

Relaying performance on 500 kV lines for a system containing GBDs in the HV transformers has been investigated. It has been found that the existence of the GBDs which were based on two benchmark-type model designs had no impact on the relaying performance. Both negative sequence and zero sequence polarizing current could be used successfully in distance protection schemes for the faults investigated and no anomalies were apparent on the operation of the relays.

Potential for resonance for the two types of GBDs was also explored for both steady-state and faulted system conditions. A somewhat unexpected result was that resonance was not necessarily the prime cause for concern regarding possible overvoltages across the GBD, particularly for the steady-state situation. Type I design, the 1.03 ohms device fared much better in overvoltage performance under steady-state, while type II design, at 43.2 ohms shows a potential to approach limiting values in the overvoltage performance.

Both types however under faulted conditions offer extremely high voltages across them, and proximity to resonance only aggravates this. It is imperative that the possibility of leaving these devices unprotected, such as may arise from a fail-opened MOV on a previous fault, be eliminated and a backup protective spark gap made available for all designs.

Finally the energy sustained in the MOVs of Type I (the 1.03 ohm GBD) was found to exceed the design ratings in many of the simulated faults. This corroborates similar conclusions regarding these devices in previous investigations, and as such, and an obvious conclusion is that a design change is required for this type before it can be applied with assurance as to reliability of operation.

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