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Grid Modernization and System Upgrade Impacts on a Three-Wire Distribution System Serving Critical Military Loads

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SUMMARY

Power systems continue to modernize with constant demand for newer technologies. Legacy power systems (such as three-wire distribution) can present additional challenges beyond those of a typical four-wire distribution system. This paper explores the theory of effectively grounded systems, coefficient of grounding, arrester sizing, fault current magnitudes, protection schemes, and protection coordination when considering grid modernization in either a three- or four-wire system. The paper discusses these challenges and aims to provide solutions including a real-world example of upgrades to a 13.8 kV three-wire distribution system serving critical military loads.

Three-wire systems contains only A, B, and C phases, whereas four-wire systems have an additional neutral (N) conductor connection to provide a continuous ground reference and carry system imbalances. Three-wire system imbalances result in voltage rises on other phases, whereas four-wire systems do not have this problem. The voltage rise seen on other phases can cause problems throughout the system.

Three-wire systems do not have a neutral and need to establish a grounding reference by other means. Typically, zig-zag grounding transformers are used to establish a grounding reference and serve to supply ground current to assist in protection schemes. Locations of grounding sources also play a role since the system configuration changes when islanded. Protection schemes may need to consider ground current directionality and coordination based on the grounding source location for certain islanding scenarios.

A 13.8 kV military installation in the Southwestern United States was fed off a delta tertiary winding of the local utility's power transformer. This paper discusses specific examples of the challenges and the steps forward to keep the critical loads at this military installation in service as well as maintaining an appropriate design with the rest of the facility, despite changes the system was not designed for.

KEYWORDS

Three-wire, four-wire, distribution systems, ungrounded, solidly grounded, effectively grounded, coefficient of grounding (COG), surge arresters, relay coordination.

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1. Introduction

Power systems continue to modernize with constant demand for newer technologies such as microgrids, islanding schemes, and distributed energy resources. Legacy power systems (such as three-wire distribution) can present additional challenges beyond those of a typical four-wire distribution system with an established system neutral. As such, system upgrades are often the first step to grid modernization but may not satisfy all the system requirements. This paper explores the theory of effectively grounded systems, coefficient of grounding, arrester sizing, fault current magnitudes, protection schemes, and protection coordination when considering grid modernization in either a three- or four-wire system. The paper will examine these challenges and aim to provide solutions including a real-world example of upgrades to a 13.8 kV three-wire distribution system serving critical military loads.

A traditional three-wire system contains only A, B, and C phases, whereas a four-wire system has an additional conductor designated as a neutral (N) connection to provide a continuous ground reference and carry system imbalances. Since three-wire systems do not have a neutral, current imbalances from unequal loading and/or ground faults result in voltage rises on the other phases. For example, an A-phase-to-ground fault results in B- and C-phase voltages to increase. A four-wire system will not experience these same voltage rises as the neutral provides a steady ground reference. The voltage rise seen on other phases can cause equipment damage throughout the system if the equipment is not rated properly. For instance, surge arresters are sized considering both maximum continuous overvoltage ratings and maximum duty-cycle voltage – fault condition ratings – when determining their appropriate size. During an imbalance or fault condition, a three-wire system experiences a voltage increase on the other phases and the magnitude increase needs to be considered to prevent the arrester from misoperating.

Since three-wire systems do not have a neutral, they may need to utilize additional grounding references. For instance, zig-zag grounding transformers are physically connected such that they supply ground current (zero sequence current) to assist in protection schemes and help to effectively ground a system. The coefficient of grounding (COG) is a calculation used to determine a system's grounding classification by comparing the maximum line-to-ground voltage on the unfaulted phases to the system's nominal line-to-line voltage rating. An effectively grounded system has a COG that does not exceed 80%. Locations of grounding sources also play a role when considering islanding scenarios as the COG will change when islanded. Additionally, the protection scheme may need to consider ground current directionality and coordination based on the grounding source location for certain islanding scenarios. Consequently, as a system adds grounding references to meet the COG requirements, the maximum ground fault current inevitably increases and can lead to overdutied equipment, protective coordination issues, and safety concerns.

A 13.8 kV military installation in the Southwestern United States until recently was fed off a delta winding of the local utility's power transformer. Historically, a three-wire delta system had been installed possibly to allow portions of the system to continue to operate with a single phase out of service. However, with upgrades over the years, including the addition of zig-zag grounding transformers at the main substation, the system became effectively grounded, but at a single point. With the addition of a photovoltaic solar facility to increase reliability, the local transmission utility upgraded the power transformers feeding the military facility, introducing a solidly grounded wye at the source. The military is now continuing to explore the use of additional local generation and microgrids, which pose challenges as the system ground disappears when the three-wire system is islanded. This paper will discuss specific examples of the challenges and the steps forward to maintain proper system grounding for the microgrids and islanding situations that may be necessary to keep the critical loads at this military installation in service, regardless of the overall power system condition, as well as maintaining an appropriate design with the rest of the facility despite changes the system was not designed for.

2. Grounding Considerations and Effectively Grounded Systems

Grounding is an essential principle in all aspects of power system analysis with the objective of minimizing transient overvoltages to meet safety requirements. There are four types of system grounding methods: ungrounded, high impedance, low impedance, and effective or solidly grounded. Each method has its own advantages and disadvantages, but this paper only examines ungrounded and effective or solidly grounded systems. Since the military facility was previously a three-wire system fed off a delta tertiary, it was an ungrounded system. With the installation of the grounding banks and later the transformer replacement and the 13.8 kV connection changing to a solidly grounded wye connection, the system was no longer considered ungrounded.

At some point, the military facility added zig-zag grounding transformers to establish a grounding reference and to effectively ground their ungrounded system. There are multiple methods used to determine if a system is effectively grounded, IEEE Std 142 examines two ratios shown below. The first ratio compares the system's zero sequence reactance (X_0) to the positive sequence reactance (X_1) and the second ratio compares the system's zero sequence resistance (R_0) to the positive sequence reactance (X_1).

$$\frac{X_0}{X_1} \leq 3.0 \quad \text{and} \quad \frac{R_0}{X_1} \leq 1.0$$

If the ratio of zero sequence reactance to positive sequence reactance is less than or equal to 3.0, the system is effectively grounded. If the ratio of zero sequence resistance to positive sequence reactance is less than or equal to 1.0, the system is effectively grounded.

Another method is to calculate the coefficient of grounding (COG). This method compares the maximum line-to-ground voltage on the unfaulted phases to the system's nominal line-to-line voltage rating and if the ratio is less than 80%, the system is considered effectively grounded.

Considering the COG requirements with the new wye-grounded main power transformer replacement, the system was studied without all existing grounding transformers to determine if the system is effectively grounded. Since this substation is in the Southwest, the military had installed solar generation to serve part of their system load. Since solar generation output can vary greatly depending on the time of day, the scenarios where solar generation is completely offline and where it is at full capacity were both analyzed. Additionally for completeness, SLG and DLG faults were analyzed. Both zero-impedance and moderate-impedance faults were considered for the DLG cases because fault impedance can change the unfaulted phase voltage value in the DLG case, as opposed to the SLG case where they are independent. The impedance used for the moderate-impedance DLG fault was 25 ohms. This was found to be the impedance that generated the highest unfaulted voltage increase.

The following equation from IEEE Std C62.92.4 was used to find the COG:

$$\text{COG} = \frac{V_{LN}'}{V_{LL}} \times 100\%$$

V_{LN}' is the maximum line-to-ground voltage on the unfaulted phases. The system is effectively grounded when COG < 80%. **Error! Reference source not found.** below lists the V_{LN}' and COG values found for each analyzed scenario with a nominal voltage of 13.8 kV.

Table 1: Coefficient of Grounding Results						
	SLG Fault		DLG Fault		DLG Fault with 25 Ohm Impedance	
Solar Generation	Unfaulted Phase Voltage (kV)	COG	Unfaulted Phase Voltage (kV)	COG	Unfaulted Phase Voltage (kV)	COG
Online	9.43 kV	68%	8.51 kV	62%	9.89 kV	72%
Offline	8.23 kV	60%	7.42 kV	54%	8.61 kV	62%

The study concluded that with the main power transformer replacement and all grounding transformers offline, the system remained effectively grounded as defined by IEEE Std C62.92.4. Note that the removal of the grounding transformers also reduces the maximum ground fault current but that will be discussed in a later section.

Furthermore, if the military ever plans to install generation on a distribution feeder and intends to operate in an islanding scenario, a separate COG study is required. Since the connection back to the main transformer would be lost with the feeder breaker open and the feeder islanded, the islanded system would need to be effectively grounded independently from the military's distribution system studied in **Error! Reference source not found.**. The process of verifying if the islanded configuration remains effectively grounded is the same described above. However, with further adoption designs tend to move towards standardization. For instance, grounding references are either provided through the solidly grounded generator(s) or the transformer(s). If the generator is not solidly grounded, the associated transformer (whether step-up or grounding bank(s)) provides the ground reference. Also consider that additional ground references will only improve the overall system COG under normal conditions.

3. Voltage Considerations and Surge Arrester Sizing

Three-wire systems do not have a neutral, thus current imbalances from unequal loading and/or ground faults result in voltage rises on the other phases. The resulting voltage rise on the other phases of a truly ungrounded system is roughly 1.73 and indicates equipment insulation should be sized for line-to-line voltages. Note that as an ungrounded system moves closer to an effectively grounded system, the magnitude voltage rise in the other phases is reduced. Surge arresters also need to consider the voltage rise during equipment sizing to avoid misoperations. Transient overvoltages in three-wire systems can also lead to high voltages which can breakdown equipment insulation resulting in faults.

IEEE C62.11 defines surge arresters as protective devices designed to limiting surge voltages on equipment by diverting surge current and returning the device to its original status. Surge arresters can repeat these functions as specified. As such, surge arresters are widely used through the power system to protect against undesirable surge voltages. These surge voltages occur from events such as lightning strikes to switching surges and temporary overvoltages and surge arresters are sized to deal with these surge voltages appropriately. Surge arresters are sized considering their maximum continuous overvoltage rating (MCOV) and their maximum duty-cycle voltage. MCOV is typically sized assuming +/- 5% system voltage, for a 13.8 kV solidly grounded system the calculated MCOV is roughly 8.37 kV. Note if a system is run at or above 105% voltage regularly, consider sizing up the arresters to reduce the risk of nuisance operation. Refer to Table 2 below, which lists some common distribution voltages and their recommended MCOV ratings depending on the system configuration.

Table 2: Arrester Sizing Reference					
Typical System Voltages (kV rms)			Typical Arrester MCOV Ratings (MCOV) kV rms		
Nominal L-L Voltage	Maximum L-L Voltage	Maximum L-G Voltage	Solid Multi-Grounded Systems (4 Wire)	Uni-Grounded Systems (3 Wire)	Impedance Grounded, Ungrounded, and Delta Systems
12.0	12.6	7.28	7.65	10.2	
12.47	13.1	7.57	7.65	12.7 (7.65)	
13.2	13.9	8.01	8.4	12.7 (8.4)	
13.8	14.5	8.38	8.4	12.7 (8.4)	15.3 (8.4)
20.8	21.8	12.6	12.7	15.3 (12.7)	

As three-wire delta systems generally have equipment with higher MCOV than solidly grounded systems, the military did not need to update existing arrester sizes. However, if you consider the voltages shown in **Error! Reference source not found.**, the maximum SLG voltage is 9.43 kV and the maximum DLG voltage is 9.89 kV. These arresters approach the 10 kV (8.4 kV MCOV) fault rating but are likely still a reasonable choice.

4. Fault Current Considerations, Relay Coordination, and Protection Schemes

Replacing the main system 25/33.3/41.7 MVA transformer with a 30/40/50 MVA transformer resulted in increasing maximum available fault currents. Note from earlier that by also changing the transformer's 13.8 kV connection from delta to wye-grounded, the system's ground reference changed, resulting in additional ground fault current. Based on the results of the COG study, the grounding transformers were no longer necessary to have an effectively grounded system and their respective ground current contributions can be ignored. These system changes resulted in new available fault currents seen by the substation relays and necessitated a coordination review. Refer to Table 3 below to see how the maximum available fault current values increased with the transformer replacement even with all grounding transformers offline. In addition to the equipment at the substation, distribution equipment ratings throughout the distribution system needed to be verified.

Table 3: Maximum Available Fault Current		
Fault Type	Previous Maximum Fault Current (A)	New Maximum Fault Current (A)
Three Phase Fault	6,500	7,451
Single Line to Ground Fault	6,891	9,178

The adjacent transmission-utility substation feeds the new 30/40/50 MVA 138 kV/13.8 kV transformer which feeds two main 13.8 kV buses. Four total 13.8 kV feeders feed the military substation which consists of two sets of switchgear each split in half by a tie breaker, resulting in four main buses. Since the fault current increased enough, most relay pickups and time dials needed adjustments to maintain a proper coordination time interval (CTI) in accordance with Table 15-3 from IEEE Std 242, shown below as Figure 1. With no upstream coordination margin, the bus tie relays were set the same as the main feeder relays as a bus fault is unlikely to happen in the switchgear between the two relays and resulted in enough room to achieve required CTI downstream and at the distribution feeder relays with their next downstream protective device.

Downstream	Upstream			
	Fuse	Low-voltage breaker	Electro-mechanical relay	Static relay
Fuse	CS[b,c]	CS	0.22 s	0.12 s
Low-voltage circuit breaker	CS[c]	CS	0.22 s	0.12 s
Electromechanical relay (5 cycles)	0.20 s	0.20 s	0.30 s	0.20 s
Static relay (5 cycles)	0.20 s	0.20 s	0.30 s	0.20 s

[a]Relay settings assumed to be field-tested and -calibrated.
[b]CS = Clear space between curves with upstream minimum-melting curve adjusted for pre-load.
[c]Some manufacturers may also recommend a safety factor. Consult manufacturers' time-current curves.

Figure 1: IEEE Std 242 Table 15.3 – Minimum CTIs

As earlier referenced, if the military were to add generation to one of their distribution feeders with the intention of islanding from the system if needed, another coordination review would be necessary. The addition of distributed generation downstream from the substation complicates the previous radial distribution system by adding another source and additional system configurations to consider. Generally, adding directional supervision to the existing overcurrent relays is effective and a reliable solution in this instance. However, every distribution system is different based on their electrical topology and with increasing demand and adoption of new distributed energy resources, new creative and innovative solutions will rise to meet the challenge.

5. Conclusion

Grid modernization and system upgrades are inevitable, and it is imperative to understand power system fundamentals to ensure successful implementation. This paper outlined some of the fundamentals like the theories of effectively grounded systems, coefficient of grounding, surge arrester sizing, fault current magnitudes, protection schemes, and protection coordination in either a three-wire and four-wire system. Additionally, these concepts were explored with a real-world example regarding system upgrades to a 13.8 kV three-wire distribution system serving critical military loads.

Understanding what grounding method, such as ungrounded and/or solidly grounded, a system uses is critical in every aspect of the system's design. For instance, the military facility previously required zig-zag grounding transformers to meet the effectively grounded criteria. An effectively grounded system has a COG that does not exceed 80%. Surge arresters are sized based on MCOV and their maximum duty-cycle voltage. An ungrounded system can experience voltage rises on unfaulted phases up to 1.73 times their nominal voltage, whereas a solidly grounded system would not, and the surge arresters need to be sized appropriately to avoid misoperation. Note these voltage considerations should be applied to all system equipment insulation, not just surge arrester ratings. Even when effectively grounded, the lack of the system-wide neutral presents a scenario where line-to-neutral voltage rise may be higher than a true four-wire system.

All transmission and distribution systems require equipment upgrades over time. These upgrades can be the result of standard equipment approaching the end of its life cycle or an adoption of a new technology. Consider the military facility replacing their main transformer with a larger transformer and with a different connection so the facility was no longer served off a delta tertiary. This change altered their system drastically such that zig-zag grounding transformers were no longer required for the system to be effectively grounded and their respective fault current contributions can be ignored. Also recall that the new transformer is larger and thus has more available fault current. These considerations and changes in fault current, required verifying protective relaying coordination and equipment ratings. Note that it is good practice to verify relay coordination with any significant change in a system's available fault current. Typical relay protection schemes and coordination philosophies will need to be examined with the adoption of newer technologies and further integration of DERs.

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