Application Guidelines for Transformer Connection and Grounding for Distributed Generation: An Update

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Abstract - Selecting proper transformer winding connections along with the neutral grounding has played an important role in the design and applications of power system protection scheme at all levels for many decades. This paper addresses how a transformer connection and the grounding currently utilized in various distributed generation projects can have a considerable impact in the future on a utilities distribution system.

Index Terms — Grounding, Distributed Generation, Protection, Safety, Transformer Connection, O & M

I. INTRODUCTION

Grounding of electrical power systems is a very important consideration when designing new systems or upgrade or retrofit existing systems with new or additional equipment. This has become an intriguing and challenging task with the proliferation of distributed generation (DG) in the conventional power distribution systems (defined here typically for voltages 12.47kV and below). Power system is grounded so that they are able to control the voltage with respect to remote earth at zero potential [1, 2]. By having such a reference, electrical engineers can design systems to provide a path for a flow of current that will allow the detection of unwanted connections between energized conductors and ground. Grounding an electrical power system also provides the benefits of increased personnel safety and protects equipment from the harmful effects of transient over-voltages [1].

Grounding as a broad topic can be divided into two major categories: (a) focuses on the design of grounding systems for protecting personnel following the National Electric Code (NEC), and (b) focuses on the protection of equipment and the study of the effects of grounding on the operation of the electric power system [1]. This paper focuses on the latter and the importance of the transformer connections and grounding.

Traditional distribution system is radially configured. Fig. 1 depicts a simple radially fed power distribution system with single or three phase laterals where power flows from the source down to the loads (in one direction). In case of a fault, current also flows from the source to the fault.

This mode of operation is well understood by industry and utilities alike for decades and has kept distribution systems simple and relatively easy to design. Because of this simplicity, the (grounded) wye - (grounded) wye or delta- (grounded) wye transformer configuration has become standard on most distribution systems [3]. The radial distribution system has worked well in terms of reliability, selectivity for fault isolation, and its simplicity and allows operators to quickly switch components without requiring engineering analysis. However, the past decade has seen the increased usage of small generation installations (called Distributed or Dispersed Generation or DG) on customer loads on the existing distribution system. This has significantly changed the topology of the distribution system with many issues that arise from how the distribution transformer is connected and/or grounded.

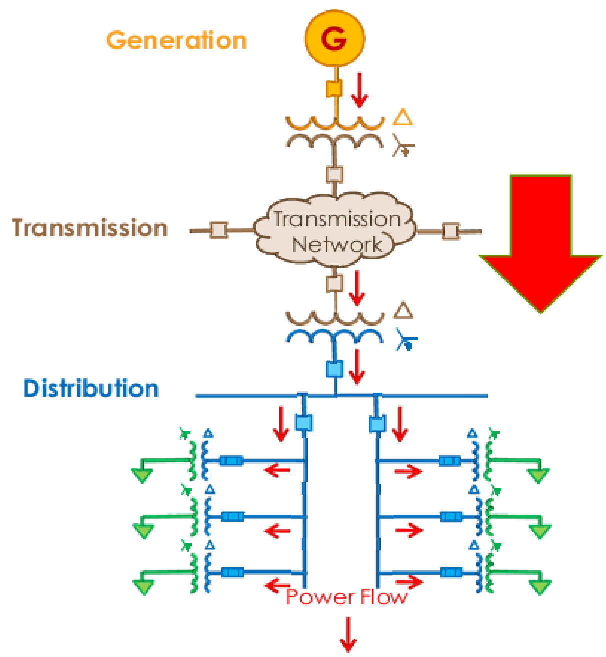

Fig. 1. Traditional Power Systems with Radial Feeders

II. TYPES OF GROUNDING

There are several methods by which a wye-configured transformer, generator, or equipment can be connected to ground. The pros and cons of various methods of grounding have been discussed on numerous papers, articles and books and are outside the scope of this paper. One of the better references is the IEEE Std. 142 (The Green Book). The various grounding methods include: (a) Ungrounded (or Capacitance Grounded), (b) Solidly Grounded, (c) High

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Impedance Grounded (Using either Resistance or Reactor) and (d) Low Impedance Grounding (Using either Resistance and Reactor) The major design considerations include (but are not limited to) in random order, minimizing the transient over-voltages caused by arcing ground fault in an ungrounded system, detection and isolation of the ground fault, sensitivity of ground fault protective devises, personnel and equipment safety, operational and design philosophy. The following table summarizes the types of grounding and the typical locations according to the IEEE Std. 142:

Table 1
Grounding Methods and Their Application [1]

Grounding Method	Typical Usage
Ungrounded: (1-3A)	Not recommended due to overvoltages (Arcing Ground Fault) and non-segreation of fault
High Impedance (Reactance): ≈ 10A	Not used due to excessive overvoltages
High Impedance (Resistance): ≈ 10A	Used on systems 600V and below where service continutity is desired
Low Reactance: (100-1,200A)	Generally used on systems either 600V and below or 15kV and above
Low Resistance: (100-1,200A)	Generally used on systems of 2.4kV to 15kV particularly where large roating machines are connected
Resonant Grounding: (Highly Resistive)	Best suited for application in most medium-voltage industrial and commerical systems that are isolated from the utility system by transformers. Mostly used in Europe
Solid Grounding: 10kA or Higher	Generally used on systems either 600V and below or 15kV and above

An "Effectively Grounded System" is one that meets the following criteria:

$$3 > \left[\frac{X_0}{X_1}\right] > 0 \quad \text{and}$$

$$1 > \left[\frac{R_0}{X_1}\right] > 0$$

Where, X_0 and X_1 are zero- and positive- sequence reactance at the fault location and R_0 is the corresponding zero-sequence resistance.

III. TRANSFORMER CONNECTIONS, GROUNDING AND DISTRIBUTED GENERATION

Various types of DG (many of them from renewable energy sources like wind, solar (PV), hydro and geo-thermal) are being installed now in distribution systems throughout the United States. As stated previously, this has changed the topology of the conventional (radial) distribution system and has a significant impact on the power system operation and safety when the system is subjected to fault conditions. Things are even more complex because the DG sources come in different design configurations like conventional rotating synchronous machines, induction generators and inverter based designs (like PV, and micro-turbine). The individual ratings of the generating source can vary from a few kW (residential PV applications) to cogeneration plant rated at 2-10MW range. Some of them (rotating machines) contribute fault currents at power frequency and others (inverter based design) do not contribute to the faults except for transient conditions. They also generate power at low-voltage to the medium voltage range depending on the size and aggregation techniques. Some DG have inertia in the form of energy stored in the rotating mass, whereas, others do not have any stored energy and no rotating mass, and with the advent of the various power electronics, the control for both real power and reactive power is very different for different applications.

Some DG is used for emergency power only. Machines of this type have a very different role and different application guidelines then conventional DG. First of all emergency generators may seldom if ever operate in parallel with the utility. Furthermore they are usually conventional synchronous generators rather than renewable sources.

With the higher DG penetration (expected at 30-40% or perhaps higher) mostly from renewable sources, the new integrated power distribution system is expected to have islanded operation (like in micro-grid or stand-alone systems). If a paralleled power distribution system becomes islanded with a fault present on the system the DG may continue to feed the fault causing significant damage unless the fault is quickly sensed and action is taken to clear the fault. In other cases the DG can cause relay coordination issues and lead to unwanted tripping. The transformer connection and the grounding with different types of DG make an impact on the design and operation of such system. It is difficult to predict the behavior of the power system when DG (rotating or inverter based) is added without some study and system simulation.

Grounding and ground fault protection design philosophy in conventional systems for industrial plants results in most of the transformers being connected delta (high-side) and wye (grounded low side). Grounding could be high resistance, low resistance or solidly grounded depending on the applications and design and operation philosophy. Delta high-side is routinely used to isolate ground faults on the low side from ground protection on the high voltage side to minimize inadvertent tripping of the high side protective devices for low-side faults. This simplifies the ground fault protection coordination and has been a standard practice for decades. Utilities also sometimes use (grounded) wye – (grounded) wye transformers in the distribution, sub-transmission and transmission systems. In these cases ground fault protection, is well coordinated to prevent ground fault relay misoperation. Standards, however, are lacking governing transformer connections; grounding and ground fault protection philosophy to be used with DG sources connected to existing distribution systems. Furthermore DG engineering is often done without the proper knowledge of grounding, sequence network, ground fault protection and safety of the distribution system as a whole.

A. *Ungrounded Transformer Connections or System*

Where the neutral of any wye connected winding is not connected to the ground (solidly or using an impedance) or where a grounded-wye grounded-wye transformer is connected to an ungrounded source results an ungrounded system results. These connections do not allow zero sequence current (ground fault current) to flow or pass from one side of the transformer to the other. The small current that will flow during a ground fault on these ungrounded systems (1-3A range) is a result of the small system capacitance.

The ungrounded wye-connected winding transformers are rarely used in power system (utility and end-users alike) due to the concerns of high transient over-voltages, over-voltage due to ferro-resonance, and steady-state over-voltages during single-line-to-ground faults [3,4]. Additionally, ungrounded sources are not used due to grounding (safety) requirements in the NEC which in many cases require a grounded power source for user connected loads. In special applications, when ungrounded systems are used, a zero-sequence ground-fault voltage detector is utilized to detect the fault and trip or alarm as appropriate based on the design philosophy.

B. *(Grounded)-Wye/ (Grounded)-Wye Transformer Connections*

This type of transformer connection can work for distribution sources. However, for a single-line to-ground fault it allows the ground-fault current to flow through and is reflected on both sides provided they are grounded at the source. Despite the fact this transformer is grounded on both sides, it does not act as a ground source.

A benefit with this connection is that there is a reduced chance of ferro-resonance occurring on either side of the transformer, and has the added benefit of no phase shift of current and voltages between the two sides. The potential downsides to this are the fact the transformer can pass zero-sequence (triplen or multiple of 3) harmonics from the DG to the utility and could cause relay coordination problems on adjacent feeders due to the fault current contribution from the DG [3,4]. If the DG source is not grounded, it can cause overvoltage during islanding from the grounded source [3, 4].

C. *Delta / (Grounded)-Wye Transformer Connection*

The delta primary grounded wye secondary configuration, as mentioned earlier, is a very common distribution transformer configuration. This connection is of particular concern to utility engineers since it is a common configuration and can also lead to over-voltages on the utility side of the transformer if the DG becomes islanded. This type of transformer configuration is also susceptible to ferro-resonance in cable fed installations as well as thermal overheating due to third harmonics from the DG. The benefits to this configuration are the fact that it blocks third harmonics from appearing on the utility system and does provide a grounding island between the primary and secondary sides as shown.

For this frequently used distribution transformer one common method is used for detecting a single line-to-ground fault on the delta side of the transformer during an islanded condition. An overvoltage relay connected phase to ground or to a zero-sequence voltage transformer on the delta side of the transformer may be used to detect and disconnect the DG for this condition. [2, 3, 4].

D. *(Grounded)-Wye / Delta Transformer Connection*

This grounding configuration is preferred by many utilities for DG interconnections. The first thing to note is that it provides a ground on the utility side of the feeder which eliminates the overvoltage concern for a utility ground fault.

This transformer connection also provides a grounding island between the primary and secondary sides of the transformer. However, it can cause issues with the secondary side which is left ungrounded. Since the secondary side probably supplies load which must be grounded to meet the NEC requirement or for operational reasons a separate grounding transformer may be required. This can significantly increase the cost of adding DG with the (grounded) wye-delta transformer.

Additionally, this transformer (independent of DG grounding) adds a ground current source on the utility feeder and can cause several issues on the utility system. This violates the radially fed idea where fault current flows only from the utility system to the fault location and creates problems with coordination of relays and system protection. Having many ground sources complicates the operation of the distribution network. This is one reason grounded connections on the utility side of the transformer are rare on radially fed distribution networks.

Another potential issue with this transformer configuration is the problems of sympathetic tripping. This is where the feeder with this transformer connection is sourcing current during a ground fault. This can be alleviated by careful protection coordination and use of directional relaying where indicated. It may require significant changes to how the utility operates and designs their system.

IV. IEEE Std. 1547.2: Grounding Recommendations Summary with DG

IEEE Std. 1547.2 describes the interconnection requirements for distributed generation resources and provides a guideline for how DG should be grounded depending on the type of distribution system. However a careful study of the applications for different scenarios is needed before blindly implementing the standard's guidelines. Table II is a summary of grounding recommendations from the Standard.

In order to facilitate application and understanding this table is presented in a way slightly different than Table I. This table shows what IEEE Std. 1547.2 recommends for grounding the DG source given an existing distribution system configuration and transformer connection. Since the majority of cases for DG integration are going to be on existing systems, this table would be a starting point for design providing some insight and design concerns with each type of transformer connection with DG. However Table II may not give the best grounding type for all situations after considerations of all system design variables.

How to deal with the increasing number of DG on the distribution network is a fairly complicated issue which doesn't lend itself to simple or quick universally applicable methods. As discussed, there are too many variables and unknown situations to allow generalized rules and it is difficult to define all the scenarios and modes of operation seen in existing distribution systems. Many customers do not have the ability to pay for new transformers or complicated relaying schemes. The grounding and protection system chosen for the DG will likely depend on the utility and customer relationship and the type of system the utility prefers. The risk that delta/grounded-wye transformers may cause over voltage damage must be weighed against the costs inherent in re-configuring the distribution network and the challenges of increasing the number of grounding sources in the system. As a minimum indepth analysis is needed before employing DG in an existing distribution network.

Table 2 [4]
Grounding Recommendations for DG from IEEE Std. 1547.2

Primary Side Grounding	**Secondary Side Grounding**	
	Four Wire Grounded	**Three Wire Ungrounded**
Four Wire Multi-grounded	DG should be effectively grounded with respect to the primary and secondary system	DG should be effectively grounded with respect to the primary system and ungrounded or high-impedance grounded with respect to the secondary system
Three Wire Ungrounded or High Impedance Grounded	DG should be ungrounded or high-impedance grounded with respect to the primary and effectively grounded with respect to the secondary	DG should be ungrounded or high-impedance grounded with respect to the primary and secondary system

V. CONCLUSION

Adding DG to the existing power distribution system is becoming very common. If the individual DG size is small (say in kW range) and the penetration level is low (say below 10%), addition of DG doesn't cause much of a problem in most applications. However, when the individual size gets bigger (say in MW range) and the penetration level is higher (say over 20%); improper applications can cause numerous problems. In addition, in order to avoid operational and safety problems careful thought must be given to transformer winding connections, grounding of wye connected windings and DG sources. It is essential that close coordination with the connecting utility is achieved before the DG system is installed. IEEE Std. 1547 and the subsequent series provide some guidance for the issues involved, but the suggestions given are not applicable to all situations and considerable judgment and understanding is necessary to properly apply them in real world applications. Care and proper attention must be given during the design stage to ensure that the optimum grounding method and transformer type are used.

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VII. VITA

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