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New Method for Effective Grounding Design Using Grounding Transformer for the Microgrid with Inverter-based Distributed Energy Resources (DERs)

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SUMMARY

Majority of North American electric utility distribution feeders are four-wire multi-grounded systems with neutral conductor being grounded at multiple locations (typically every few poles), with effective grounding being provided by the substation transformer which is typically $\Delta - Yg$ or an autotransformer with tertiary Δ winding. Microgrids with inverter-based Distributed Energy Resources (DERs) require effective grounding to be able to operate in islanded mode and this is accomplished by installing the grounding transformer. Current IEEE standards that govern the design of grounding transformers are calculations-based and they are typically used for the power system with synchronous-based generation. As such, these standards are not well-suited for microgrids with inverter based DERs that operate in islanded mode, as they do not provide the optimum grounding transformer design characteristics. This paper presents a new simulation-based grounding transformer design method for microgrids with inverter-based DERs and compares which to calculation-based grounding transformer design methods governed by IEEE Std. C57.32 [1], IEEE Std. C62.92 [2] and IEEE Std. 1547.8 [3] (not approved yet) to validate the proposed design approach.

KEYWORDS

Microgrid, effective grounding, coefficient of grounding, inverter-based DERs, grounding transformer, ground faults, open phase conditions.

1. Introduction

According to the Department of Energy (DOE) microgrid definition, microgrid is" a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid". A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island-mode." [4]. Majority of North American electric utility distribution feeders are four-wire multi-grounded systems with neutral conductor being grounded at multiple locations, with effective grounding being provided by the substation transformer which is typically $\Delta - Yg$ or an autotransformer with tertiary Δ winding. Neutral wire is grounded throughout on the distribution feeder approximately every two or three poles, to prevent the voltage rise on the system neutral. When microgrid operates in grid connected mode, its effective grounding is provided by the substation transformer Yg side. However, the type of DER within the microgrid as well as the configuration of the connecting transformer has a major impact on security and reliability of feeder protection and relaying scheme as well as the temporary overvoltage during the ground fault conditions. There are five basic factors that are typically considered when designing the effective grounding scheme for the power system:

1. voltage ratings and degree of surge voltage protection available from surge arresters
2. limitation of transient line-to-ground over-voltages
3. security (relays should not trip when there is no fault on the feeder, to avoid nuisance tripping) and reliability (relays should trip when they detect the fault) of the ground-fault relay protective schemes
4. ground fault magnitude current limitation, and
5. safety.

There are two requirements that must be met for the transformer in order for it to provide the effective grounding:

1. transformer winding on the voltage level where the ground is required must be connected in Y, where the neutral is connected to the earth, and
2. " The impedance of the transformer to ground fault current must be significantly lower than the impedance of the connection between the neutral and earth such that this neutral impedance governs the selection grounding mode" [5]. As a result, the only winding on the opposite side of Y that satisfies this requirement is Δ.

In a traditional power system, effective grounding is provided by the substation transformer, which is traditionally $\Delta - Y_G$, with Δ winding being on the high side, and Y_G connection being on the low side or the side where effective grounding is needed. In some cases, autotransformers with tertiary Δ winding are used to provide the effective grounding. Key lesson learned in this case and one of the biggest misconceptions of effective grounding is that simply having the neutral wire connected to the ground on the feeder is not the only requirement for effective grounding.

Design of effective grounding for microgrids has several major challenges, but two of the most important ones are ground fault currents, and temporary over-voltages (ToV). To show the impact of DER transformer configuration on the feeder ground fault current level, assume that the one-line diagram of the traditional substation is shown as Fig. 1 below. First, assume that DER recloser is open and the DER is not connected to the feeder. Any unbalance on the system results in the current flow from the neutral of the substation Δ-Y_G transformer to the ground (on the Y_G) side. Following, assume that phase A line-to-ground (LG) fault occurs on the feeder. From protection and control theory, any ground fault has three sequence networks: positive-, negative- and zero-sequence network. As shown on the figure above, substation Δ-Y_G transformer traditionally provides the zero-sequence path for the ground fault current. During the ground fault condition, the fault current flows back to the substation transformer and reverses its direction (now, it flows from the ground to the neutral of the Y_G side of the substation transformer). This fault current is then detected by the substation and feeder relays, and subsequently, trip command is issued by the relay to clear the fault. Ground fault current, as seen by the substation breaker relay.

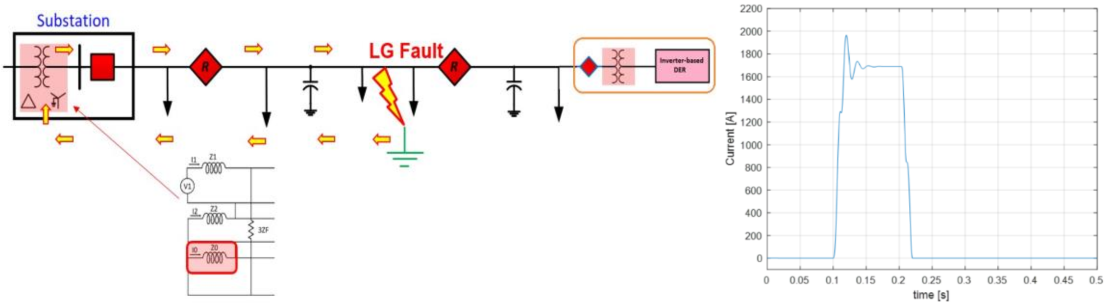

Fig. 1: Substation feeder with DER and ground fault current being cleared by the relay

Second, assume that the DER is connected to the substation feeder by closing the DER recloser. Figure 2 below shows the equivalent zero-sequence circuit for each of the different transformer configurations: Y_G-Y_G, Y_G-Δ, Y_G-Δ with neutral resistor, Y_G-Y, Δ- Δ and Y-Δ.

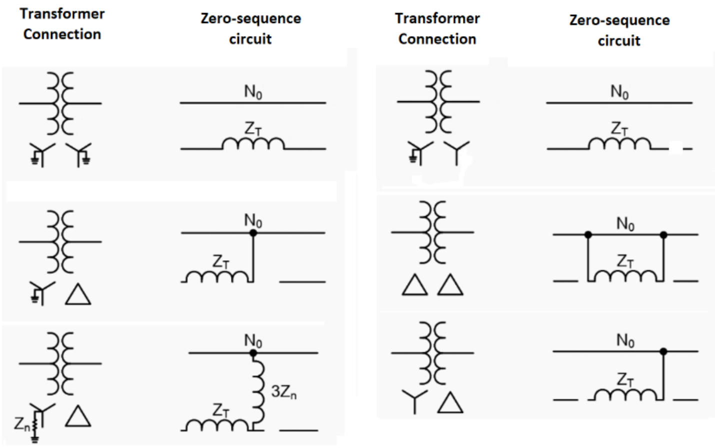

Fig. 2: Zero-sequence circuits for different transformer configurations

If the DER transformer configuration is Y_G-Δ, then substation breaker will see significantly lower fault current, and depending on the size of the DER, its fault current contribution, fault location and fault impedance, substation breaker might not trip for a ground fault as seen on Fig. 1. The reason why this happens is because during the ground fault, Y_G-Δ transformer provides the additional zero-sequence path for the fault current. In this case, instead of having the ground fault current flow back to the substation, the fault current splits at the fault location and portion of the fault current starts flowing towards the DER's Y_G-Δ transformer as seen on the Figure 3.

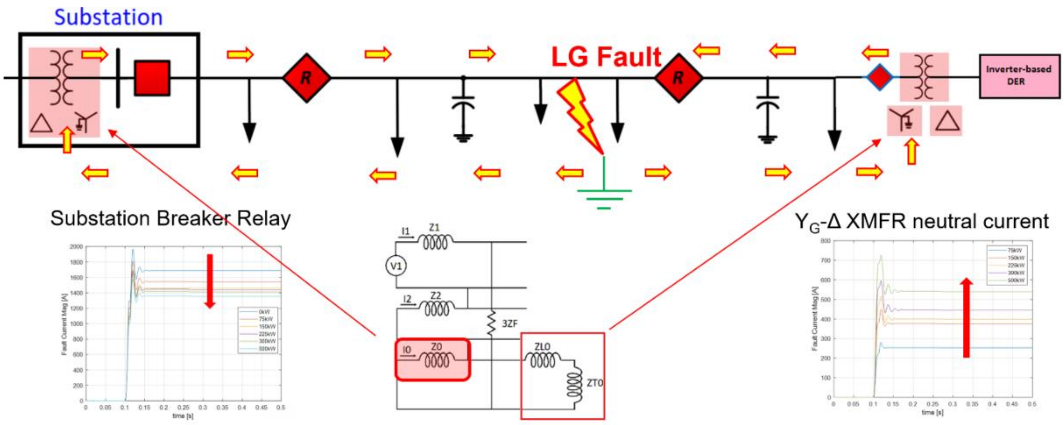

Fig. 3: Fault current as seen by the substation breaker relay with DER with Yg−Δ transformer

In order to solve this problem, changing DER transformer configuration from Y_G-Δ to Y_G-Y provides preferred solution, because Y_G-Y transformer configuration does not provide path for zero-sequence fault current. As noted before, ground fault current represents only one challenge with the design of effective grounding. Second challenge in this case is the temporary overvoltage (ToV). During ground fault, voltages on the un-faulted phases increase due to the loss of ground source (substation transformer). If DER is connected to the feeder using transformer configuration other than Y_G-Δ, then during ground fault occurrence on the feeder, upstream breaker/recloser will open to clear the fault. In this case, the DER can stay energized up to 2 seconds (per [7]) and during this time, the portion of the feeder with DER and ground fault will not be effectively grounded. Since feeder devices are rated for LG voltages, exposing these devices to LL voltages can cause their damage and/or failure. If size of DER is large enough that this is a possibility, then small grounding transformer is installed next to DER using options provided in [3]. However, this grounding transformer should not be used to provide effective grounding for microgrid that this DER is part of, because grounding transformers designed to prevent ToV have significantly lower rating than grounding transformers designed to provide effective grounding for microgrid with inverter based DERs.

2. Grounding Transformer Design Using Existing Standards

In order to properly design the effective grounding for the microgrid with inverter based DERs, it is necessary to install a grounding transformer to the microgrid. This transformer is only connected when microgrid operates in islanded mode, while it is disconnected when microgrid is connected to the grid. Grounding transformer serves several purposes within the microgrid:

1. provides effective ground reference for the microgrid,
2. enables the design of more reliable and secure microgrid protection and control scheme,
3. enables seamless grid synchronization,
4. prevents ferro-resonance from occurring within the microgrid,
5. reduces over-voltages that result from open phase conditions.

There are several standards that govern the design of effective grounding of the power system: IEEE Std. C57.32, IEEE Std. C62.92.1-6 and IEEE Std. 142. IEEE Std. C57.32 standard describes the requirements, terminology and testing of neutral grounding devices, such as grounding transformer. IEEE Std. C62.92.1-6 standards refers to the application of neutral grounding in electric utility system for synchronous generator systems, generator auxiliary systems, distribution, transmission and sub-transmission systems and systems supplied by current-regulated sources. IEEE 142 refers to the effective grounding on systems less than 1000V. There are six main design parameters that are used to design grounding transformer: construction type, voltage, zero-sequence impedance (Z_0), neutral steady-state current, neutral fault current withstand rating and kVA rating. For the purposes of analysis, a microgrid as shown on Fig. 4 below with 500kVA battery energy storage system (BESS) and fault duty of 2.4p.u. and 750kV solar farm (PV) with 1.5p.u. fault duty as the only two Distributed Energy Resources (DERs). Microgrid has a total load of 1000kVA with power factor of 0.8 and total connected transformer capacity of 2000kVA.

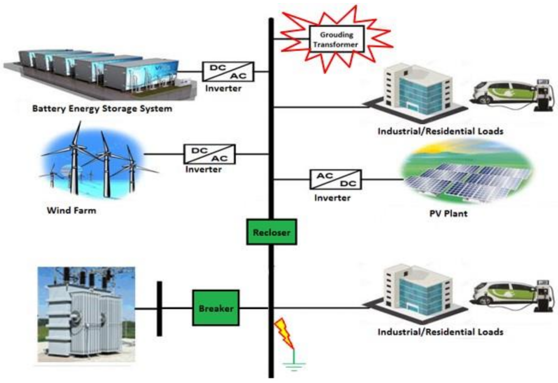

Fig. 4: Microgrid - One-line diagram

Grounding transformer will be designed using IEEE Std. C62.92 calculations-based method and will be compared to the new proposed simulations-based method.

2.1. Grounding transformer design using IEEE Std. C62.92

IEEE Std. C62.92 has been widely used today for the design of neutral grounding in electrical utility systems, where majority of the generation is in form of synchronous based generators. This standard does not specifically addresses the neutral grounding in microgrids with inverter-based DERs. As such, using this standard to design the grounding transformer for microgrid with inverter based DERs can result in an inadequate solution. This section outlines the design of grounding transformer using IEEE Std. C62.92.

1. *Construction type*: grounding transformer comes in two forms: Y_G-Δ and "Zig-Zag". "Zig-Zag" transformer is more efficient than Y_G-Δ transformer, and it can be rated lower by a factor of $\sqrt{3}$ therefore reducing the cost. However, from practical standpoint, given the levels of fault current and total microgrid DER capacity, chosen construction is Y_G-Δ, since vendors rarely design and build "Zig-Zag" transformer in low kVA range.
2. *Primary and secondary voltage*: microgrid primary voltage is 12.47kV in this case, which determines the grounding transformer primary voltage. Secondary voltage can be any voltage level and the design engineer can choose this voltage based on her/his own preference, since secondary side of transformer traditionally does not carry any load. In this case, 480V has been chosen for the secondary voltage.
3. *Impedance (Z_0)*: First, impedance and current base values are calculated as:

$$Z_{BASE} = \frac{V_{DER}^2}{S_{DER}} = \frac{12.47kV^2}{1250kVA} = 124.4\Omega \,;\, I_{BASE} = \frac{S_{DER}}{\sqrt{3}*12.47kV} = \frac{1250kVA}{\sqrt{3}*12.47kV} = 57.87A$$

Maximum fault duty contribution from both BESS and PV is calculated as:

$$S_{FAULT\ DUTY} = 2.4pu * 500kVA + 1.5pu * 750kVA = 2325kVA$$

Positive (Z_1) and negative (Z_2) sequence impedances are then calculated as:

$$Z_1 = Z_2 = \frac{S_{DER}}{S_{FAULT\ DUTY}} = \frac{1250kVA}{2325kVA} = 0.537\, p.u.$$

Ground fault current (I_{GF}) or what is commonly known as $3I_0$ is calculated as:

$$I_{GF} = \frac{S_{FAULT\ DUTY}}{\sqrt{3}*V_{PRI}} = \frac{2325kVA}{\sqrt{3}*12.47kV} = 107.65A;\ \ I_{GF}[p.u.] = \frac{I_{GF}}{I_{BASE}} = \frac{107.65A}{57.87A} = 1.86p.u.$$

Ground fault current ($3I_0$), which flows from the ground to the neutral of the Y_G side of the grounded transformer and splits evenly to all three phases (A, B and C) and these currents are designated as I_0:

$$I_0[p.u.] = \frac{I_{GF}[p.u.]}{3} = \frac{1.86p.u.}{3} = 0.62p.u.\,;\, I_0[A] = I_0[p.u.] * I_{BASE} = 0.62p.u.* 57.87A = 35.88A$$

Grounding transformer total impedance is calculated as:

$$Z_{TOTAL}[p.u.] = \frac{V[p.u.]}{I_0[p.u.]} = \frac{1.0p.u.}{0.62p.u.} = 1.61p.u.$$

Grounding transformer total impedance is the sum of positive-, negative- and zero-sequence impedance:

$$Z_{TOTAL}[p.u.] = Z_1[p.u.] + Z_2[p.u.] + Z_0[p.u.]$$

From here, per unit grounding transformer zero-sequence impedance Z_0 is calculated as:

$$Z_0[p.u.] = Z_{TOTAL}[p.u.] - Z_1[p.u.] - Z_2[p.u.] = 1.61p.u. - 0.537p.u. - 0.537p.u. = 0.539\ p.u.$$

Finally, grounding transformer zero-sequence total impedance in **Ω** is calculated as:

$$Z_0[\Omega] = Z_0[p.u.] * Z_{BASE} = 0.539p.u. * 124.4\Omega = 67.05\Omega$$

In traditional power systems, grounding transformer zero-sequence impedance Z_0 is designed to reduce the value of high fault currents on the power system. Microgrids with inverter based DERs have low fault currents to begin with, so ideal grounding transformer design should be based on minimum Z_0. This impedance has two negative impacts on the microgrid operation:

1. Impedance Z_0 results in lower fault currents, which are already low, so security and reliability of protection and relaying scheme can be compromised,
2. During ground faults, impedance Z_0 causes voltage on un-faulted phases to rise, which can result in over-voltages on those phases and coefficient of grounding to exceed 0.8, making the system not effectively grounded.

For that reason, grounding transformer for microgrids with inverter based DERs should be designed with minimum Z_0 as one of the design parameters.

4. <u>*Neutral current steady-state rating*</u>: this value is obtained based on the table from IEEE Std. C57.32 and it is determined based on the short-term ground fault current grounding transformer rating as shown in Table I below.

TABLE I: Grounding transformer neutral current steady-state rating

Rated time	Continuous duty [% of thermal current rating]	I_{GF} = 107.65A
10-seconds	3%	3.23A
1-minute	7%	7.54A
10-minutes	30%	32.30A
Extended time	30%	32.30A

As seen from the table, neutral current steady-state rating changes as a function of the grounding transformer neutral fault current withstand rating if the grounding transformer is built according to IEEE Std. C57.32.

5. <u>*Neutral fault current withstand rating*</u>: this current was calculated based on the calculations described above and it is 23.61A.

6. <u>*kVA rating*</u>: Grounding transformer fault current kVA rating is based on the neutral fault current using two different formulas, depending on the chosen configuration. In this case, for Y_G-Δ configuration, KVA rating is calculated as:

$$S[kVA] = \frac{V_{LL} * I_N}{\sqrt{3}} = \frac{12.47kV * 107.65A}{\sqrt{3}} = 775kVA$$

Note that the kVA rating for ”Zig-Zag” transformer is 1/ 3 less than the rating for Y_G-Δ construction type.

2.2. Grounding transformer design using new proposed method

The new method for the design of grounding transformer is simulation-based iterative process. In order to successfully perform the analysis, it is necessary to know some of the technical characteristics of few grounding transformers that are potential candidates in order to find the optimum solution.

1. *Construction type*: similar to before, grounding transformer construction is Y_G-Δ.
2. *Primary and secondary voltage:* also similar to before, primary and secondary voltages for grounding transformer are chosen to be 12.47kV – 480V
3. *Impedance Z_0 and Neutral fault current withstand rating:*

   This step represents the major difference between the existing standard and new method being proposed in this article. The impact of grounding transformer zero-sequence impedance Z_0 is two-fold:

   a. Z_0 only has impact on ground fault currents (LG and LLG)
   b. higher Z_0 impedance results in lower ground fault currents
   c. higher Z_0 at the same time results in higher voltages on unfaulted phases during the ground fault, therefore resulting in higher CoG.

New proposed method for determining the impedance Z_0 and neutral fault current withstand rating of grounding transformer is based on the iterative process, where at first, several different grounding transformers are chosen with different zero-sequence impedance values Z_0 as shown in Table II.

TABLE II: Grounding transformer characteristics

Rating [kVA]	V_{PRI} [kV]	V_{SEC} [V]	Z[%]	Z_0[%]	X/R [ratio]
75	12.47	480	2.15	1.25*Z	1.25
150	12.47	480	2.75		2.25
225	12.47	480	3.75		4.25
300	12.47	480	4.50		5.25
500	12.47	480	5.90		5.75

Data in Table II refers to transformers that are grounding sources, rather than actual grounding transformers, because there is no readily available public data for grounding transformers, because most of those are designed/built for a particular application on the power system, and mostly in MVA range with large Z_0 impedances. Transformer characteristics outlined in Table II, for each of the transformer ratings, continuous and neutral fault current ratings have been obtained from [7] and [8] utilizing short-circuit capability (damage) curves. In addition, distribution transformer nameplate impedances and X/R ratios can be obtained from several resources such as [9] and also, numerous transformer vendors have made this information readily available. Note that zero-sequence impedance (Z_0) value probably requires the most attention, because it can vary considerably, which depends on the construction type and number of legs (3, 4 or 5). Data for the transformers in Table 2 are based on 5 leg, core type design. Note that for example, the 500kVA Y_G-Δ transformer can be designed using traditional methods with Z=5.90% and Z_0=1.25*Z. However, if that same transformer is designed using the requirement that Z_0 is minimized, then the value for Z_0 can be in 3% range, which is one of the main proposed changes with this approach.

In order to calculate the grounding transformer design parameters, ground faults (both LG and LLG) are placed along the feeder in order to determine the maximum neutral current seen by the grounding transformer. The following algorithm describes the ground fault analysis that needs to be performed in order to determine the proper size of grounding transformer and its Z_0:

a. use 75kVA transformer and run LG and LLG fault analysis along the length of the feeder,

b. record ground fault current and CoG for each of the simulations,
c. compare the ground fault current values against the neutral current withstand rating of the 75kVA transformer and ensure that the transformer can sustain the maximum ground fault current for at least 10 seconds,
d. ensure that CoG is less than 0.8 for all ground fault current simulations, and
e. repeat steps 1-4 for 150/225/300/500kVA transformers until optimum solution is found that satisfies both conditions.

Fig. 6 shows the ground fault current during one of the simulations for different grounding transformer sizes and Ground fault analysis was done for both LG and LLG faults, and the following Table III shows the ground fault currents:

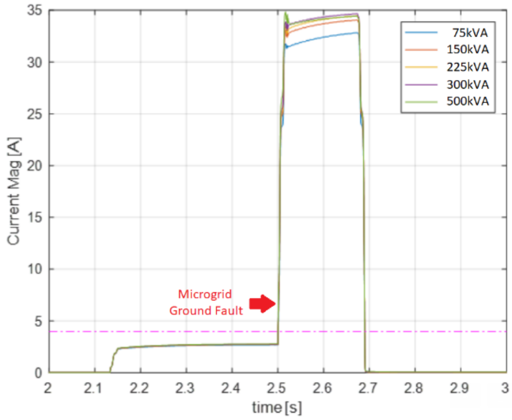

Fig. 6: Grounding transformer fault current during LG testing

TABLE III: Ground fault current analysis

Case	Fault current [A]		Neutral current [A]	
	Min	Max	Min	Max
LG fault	32.29	34.86	31.29	34.86
LLG fault	74.78	79.50	74.78	79.50

Grounding transformer neutral current withstand rating should be higher than the maximum ground fault current, so in this case, of 2.0 can be added in order to ensure that the transformer would not fail during the ground fault. From here, new grounding transformer current short-term rating can be calculated as:

$$I_{NMAX} = 2 * I_{SCMAX} = 2 * 79.50A = 159A$$

Comparing to the neutral current withstand rating of 107.65A as calculated before, the new approach provides significantly higher rating, which is verified using the actual simulations. In addition, CoG, which was measured at all locations along the feeder for all ground faults, was less than 0.8 for all simulations. However, CoG was evaluated as a function of different grounding transformer zero-sequence impedance in order to assert what would be the CoG, had grounding transformer been designed using the current standards. In addition, analysis was done with proposed Z_0 impedance of 67.05Ω using the existing standard and ground fault current in simulations was found to be 11.16A, which is significantly lower than the calculated value of 107.65A.

4. *Neutral steady-state current:* due to the phase load imbalance within the microgrid, there is a current flow between the neutral and ground on Yg side of the grounding transformer, and grounding transformer must be designed in order to carry this current continuously. New approach for calculating the steady-state neutral current I_N during the maximum microgrid phase imbalance conditions is based on using the microgrid simulations based on the maximum load imbalance of 35%. Two major standards that were used to determine the maximum load unbalance in the new proposed approach are [10] and

[11]. For a typical 3-phase induction motor, Section 14.36.5 in [10], 1% of voltage imbalance results in 6-10% of current imbalance, but traditionally used value that is based on field measurements is 7%. Standard [12] recommends that "electric supply systems should be designed and operated to limit the maximum voltage unbalance to 3 percent when measured at the electric-utility revenue meter under no-load conditions." Section 14.36 in [10], which represents manufacturers of motors and drives, states that "operation of the motor above a 5% voltage unbalance condition is not recommended" and provides also a de-rating curve for operation under voltage unbalance. Taking more stringent requirement of 5% for total feeder voltage unbalance, and if each 1% of voltage unbalance causes 7% of current unbalance, maximum load imbalance is calculated to be ±35%. This value was then taken for calculations of grounding transformer maximum steady-state neutral current.

Proposed simulations for neutral current steady-state rating are based on several operating conditions, since the output of BESS, PV and load can vary throughout the day. Proposed use cases and steady-state circulating current within the grounding transformer I_N are shown in Table IV.

TABLE IV: Microgrid normal operation with 35% load imbalance

Case	Load	PV	BESS	I_N [A]
1	1.0	1.0	VSI-ISO	2.68
2	1.0	OFF		2.68
3	0.3	0.2		5.47
4	0.3	OFF		0.83

As seen from the Table IV above, maximum neutral current simulated during the steady-state conditions is 5.47A. Since grounding transformer needs to be able to carry this current continuously, its neutral current steady-state rating has to be higher than 5.47A by some margin. Safe margin in this case is chosen to be two times the maximum neutral current I_N, so grounding transformer steady-state neutral current rating is:

$$I_N = 2 * I_{NMAX} = 2 * 5.47\text{A} = 10.94\text{A}$$

Grounding transformer rating is typically expressed in amperes, rather than in kVA. However, if needed, kVA rating formula for the steady-state neutral current grounding transformer rating is:

$$S[kVA] = \frac{V_{LL} * I_N}{\sqrt{3}} = \frac{12.47kV * 10.94A}{\sqrt{3}} = 78.77kVA$$

5. *kVA rating:* Based on the maximum ground fault current of 79.50A and grounding transformer rating of 2 times this maximum ground fault current, kVA rating of the grounding transformer is:

$$S[kVA] = \frac{V_{LL} * I_N}{\sqrt{3}} = \frac{12.47kV * 159A}{\sqrt{3}} = 1.14MVA$$

If grounding transformer is designed based on 10-second grounding fault withstand, then its steady-state rating is 3% of the neutral current withstand rating or 3%*159A = 4.77A, which is less than the required rating of 10.94A. If the rating is increased to 1-minute grounding fault withstand rating, then its steady-state rating is 7% of the neutral current withstand rating or 7%*159A = 11.13A, which is slightly higher than the required rating of 10.94A. For that reason, the optimum rating for grounding transformer in this case is 1-minute neutral current withstand rating.

3. Conclusion and future research

Implementation of proper DER transformer configuration within microgrid and design and implementation of grounding transformer present very complex engineering endeavor. This paper introduced the new methodology for designing the grounding transformer within the microgrid with inverter based DERs. The main conclusion is that the new proposed approach provides optimum grounding transformer design characteristics for microgrids with inverter-based DERs operating in islanded mode compared to the current standards-based approaches, and that the existing approach would result in grounding transformer design which would fail under steady-state conditions and result in either high ToV or not effectively grounded system. Additional challenge with improper design of grounding transformer is the energization in islanded mode, due to the inrush current, which could easily result in microgrid blackout. In addition, due to the low fault currents, it would not be possible to design secure and reliable protection and control scheme using the current standards-based approach.

TABLE V: Grounding transformer characteristics - comparison

Design parameter	IEEE C62.92	New Method
Construction	Y_G-Δ	
Voltage	12.47kV – 480V	
Impedance	$Z_0 = 67.05\Omega$	$Z_0 = 2.90\Omega$
Neutral current steady-state rating	3.23A	10.94A
Neutral current fault withstand rating	107.65A	159A
Time	10-second	1-minute
kVA rating	775kVA	1144 MVA

Because of all challenges that the design of effective grounding presents when it comes to microgrids with inverter-based DERs, the conclusion of this paper is that it is necessary to form a Working Group within CIGRE that would work on issuing a new standard for the design of grounding transformer for microgrids operating in islanded mode with prevalence of inverter-based DERs.

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