Protection and Control Challenges Associated With Implementation of Three-Phase Electric Vehicle Charging Stations

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***Abstract*—Addition of new generation sources to the power system in form of inverter-based DERs represent many challenges for protection engineers, because of the changing nature of fault current levels. Technological developments within last two decades have resulted in increased popularity of electric vehicles over internal combustion engine vehicles. In order enable the use of electric vehicles, massive electric vehicle infrastructure must be put in place. DC level 1 chargers, or what is commonly known as DC Fast chargers (DCFC), are typically 3-phase, 4-wire chargers connected to electric utility's 480V system. Depending on the internal design of the electric vehicle supply equipment (EVSE) and configuration of electric utility's step-down transformer, both electric utility and EVSE can experience relaying and power quality challenges. The material in this paper reflects the protection challenges on both electric utility and EVSE side in cases where electric vehicle charger internal auxiliary transformer has $Yg-\Delta$ configuration.**

***Index Terms*—Effective grounding, electric vehicle charging stations, system protection and control, power system faults, ground faults**

I. Introduction

SYSTEM protection and control and effective grounding design represent not only the most important, but also the most challenging aspect of the overall feeder design with the ever increasing penetration of inverter-based distributed energy resources (DERs). Addition of new generation sources to the power system in form of inverter-based DERs represent many challenges for protection engineers, because of the changing nature of fault current levels. In recent years, vast majority of new generation added the to electric utility power systems have been in form of renewables (wind, solar). These DERs are typically connected to the power system using inverters (AC/DC/AC or DC/AC) and step-up transformers. In addition to the addition of renewables, technological developments within last two decades have resulted in increased popularity of electric vehicles over internal combustion engine vehicles. Most electric vehicles today use lithium-ion battery as the main source of power, due to its higher energy density, longer life span and higher power density than most other batteries. The downside of using the lithium-ion batteries include safety, durability, thermal breakdown and cost.

Charging of electrical vehicles can represent potential challenges for the power system. Charging methods have evolved over the time and current electric vehicle charging stations fall within one of the following three levels:

1) Level 1 - these charging station are made for a 'standard' 120V US – NEMA 5-15 wall outlet. Depending on the size of the battery, this slow charging method can recharge the battery within electric vehicle overnight. It usually has no user authentication, no separate metering;
2) Level 2 - these charging stations require dedicated 240V 40A dedicated circuit and require SAE J1772 vehicle connector. Typical charging rates for level 2 charger range in 3-20kW, while most commonly charging rate is 6-7.2kW. Level 2 charger can fully charge the vehicle battery within 4-6 hours.
3) DC level 1 chargers, or what is commonly known as DC Fast chargers (DCFC). They require use of either CHAdeMO or SAE Combo (also called CCS for "Combo Charging System") plugs. These chargers can provide charging rates greater than 40kW and the charging is done using direct-current (DC) plug. These chargers are typically connected to 480V bus. Most of level 3 chargers provide an 80% charge in 30 minutes.

While level 1 and level 2 electric vehicles charging stations use single phase circuits, level 3 charging station are traditionally connected to 3Φ 480V circuits. Traditionally, electric utilities step down the primary feeder voltages (ranging from 4kV - 25kV) down to distribution voltage levels using step-down transformers (for example 12.47kV - 480V). These transformers can have different configurations, such as $Yg-Yg$, $\Delta-Yg$, etc. Implementation of each of these step-down transformer configurations at locations with 480V level 3 charging stations can have major impact on the security and reliability of the relay protection schemes as well as the power quality. The main objective of this research paper is to provide the background on protection and control considerations when installing level 3 charging stations.

II. History

Level 3 DC chargers traditionally consist of two conversion stages, one of which is a AC/DC stage, that is connected to the AC grid from which it generates regulated DC voltages and the second one, which is a DC/DC stage, which provides the DC current that is used for battery charging. There are two main architectures of level 3 DC chargers that differ based on the type of transformer used within. The first topology utilizes the low-frequency transformer and it is shown on Fig. 1. Input to this unit is a 3Φ 4-wire 277V/480V system, where neutral is grounded. The first level of overvoltage protection is provided by the surge arrester, while overcurrent protection is provided by the fuse. Charger controller is used to close the AC contactor, which energizes internal auxiliary $Yg - \Delta$ transformer (note that there is also a second transformer that is not shown here, which is traditionally rated $< 1kVA$, 480V-120V/240V used for auxiliary loads). Note that there are some variations of this internal auxiliary transformer.

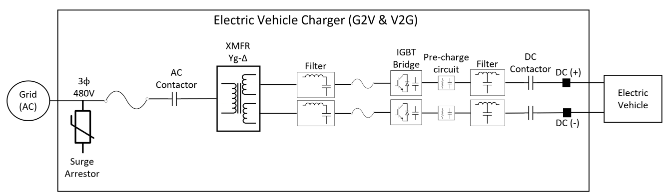

Fig. 1: Level 3 electric vehicle charging station - Low-frequency transformer

The second topology does not have the low-frequency transformer and instead, it utilizes the high-frequency DC-DC transformer and it is shown on Fig. 2.

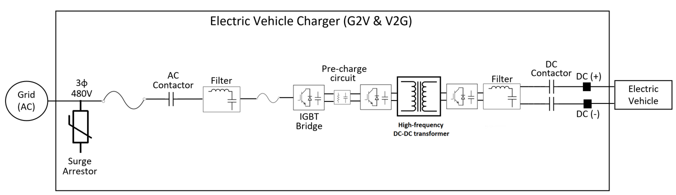

Fig. 2: Level 3 electric vehicle charging station - High-frequency transformer

Charger protection scheme within differs, depending on the charger architecture. For the high-frequency DC-DC transformer architecture, protection scheme in this case is based on monitoring the integrity of the internal insulation. For the low-frequency transformer architecture, this internal transformer can have different configurations. The material in this paper describes the system protection challenges in cases where electric vehicle charger internal low-frequency transformer has $Yg - \Delta$ configuration.

III. Methods

Electric utility distribution feeder (12.47kV) is shown on Fig. 3.

Substation, which has 110kV-12.47kV $\Delta - Yg$ transformer has been represented with its equivalent Thevenin impedance. For the purposes of this study, total of 6MVA of feeder load and power factor 0.95 were used in simulations and distributed along the feeder. Load was simulated in order to create an unbalance of approximately 5%, which is a typical value used in system planning studies. As a result, load unbalance created a current flow between the neutral and ground of the substation transformer of 15A, which was expected. The distribution feeder also has a mid-point recloser and electric vehicle charging stations used in this study were installed approximately 4.5 miles down the primary feeder, where local elementary school is located. First, study was done in order to validate the circuit model. In this case, electric vehicle charging stations were removed from the simulation. The model was imported from CYME into MATLAB/Simulink,

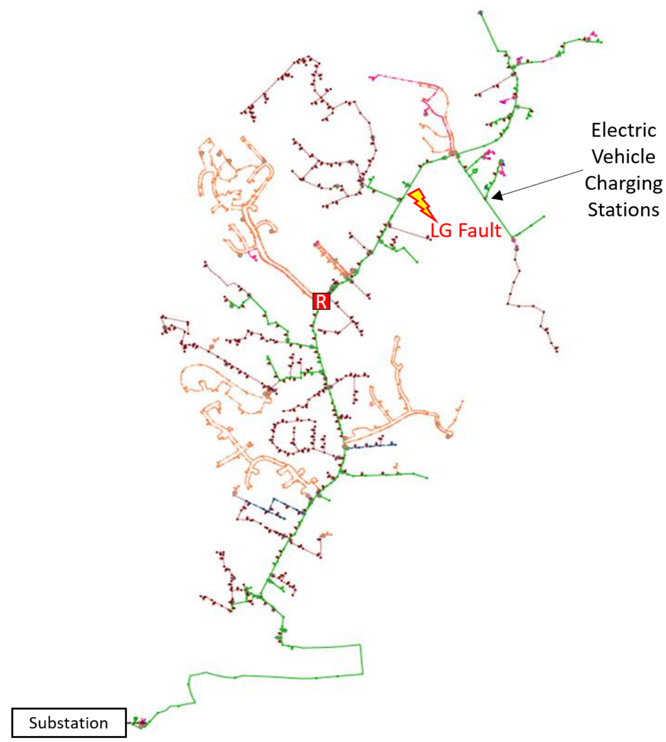

Fig. 3: Distribution feeder

and line-to-ground (LG) fault was placed downstream from the mid-point recloser. Generally accepted practice allows for 5% difference on 3Φ fault and 10% difference on ground faults. Fault current was measured to be approximately 1500A, which is well within the 10% error. Fig. 4 shows the flow of fault current as well as the equivalent positive-, negative- and zero-sequence circuit for the LG fault. As expected, the fault current flows back to the substation transformer, and then continues to flow toward the fault location. Mid-point recloser or substation breaker detect this fault and subsequently trip, therefore clearing the fault.

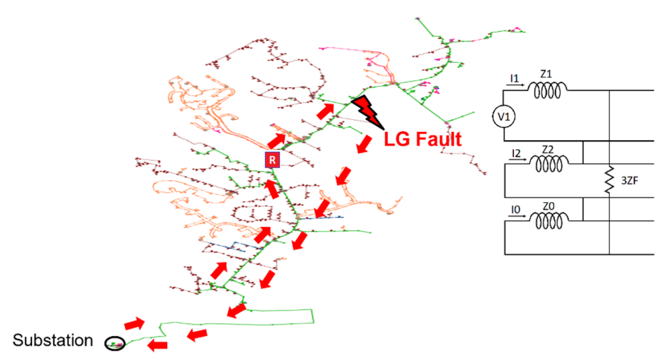

Fig. 4: Distribution feeder - model validation

Following, electric vehicle charging stations were added to the feeder model. Part of the feeder with one electric vehicle charging station is shown on Fig. 5.

The point of interconnection transformer, 12.47kV - 480V Yg-Yg and electric vehicle charging station along with some

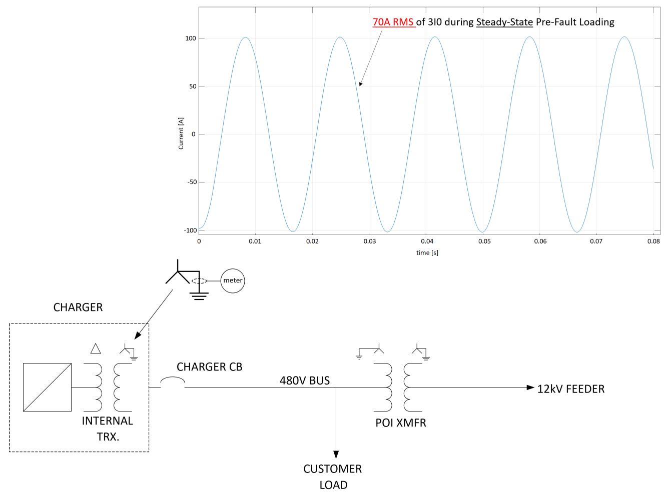

Fig. 5: Distribution feeder

auxiliary load is connected to this transformer's 480V secondary side. Meter was placed between the neutral and ground of the $Yg-\Delta$ transformer located inside the electric vehicle charger. Similar to before, feeder was first simulated with 5% unbalance, and current between the neutral and ground of internal $Yg-\Delta$ transformer within the charger was measured. As seen from the Fig. 5, under the normal operating conditions, this transformer carries of 70A of unbalance current. This current, which always flows through the $Yg-\Delta$ transformer in grid connected mode, and is always changing as a function of feeder load unbalance causes this transformer to heat and it can have major negative impact on the useful life. However, if we measure the current between the neutral and ground of the POI transformer, either on primary or on secondary side, this current is zero. So, why does this happen?

The answer to this question lies in understanding of the positive-, negative-, and zero-sequence equivalent circuits for the power system elements. Equivalent zero-sequence circuits for different transformer configurations are shown on Fig. 6.

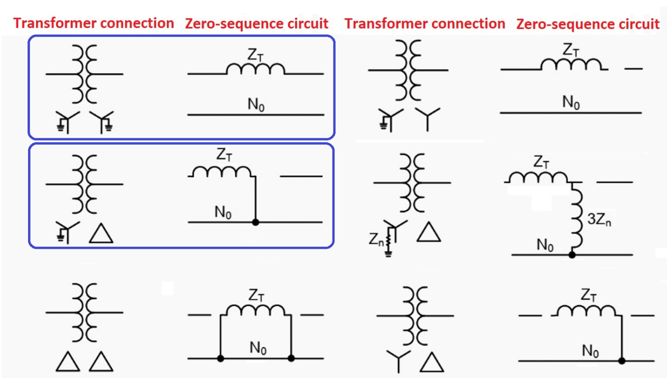

Fig. 6: Transformer equivalent zero-sequence equivalent circuits

Impedances Z_1 and Z_2 represent equivalent positive- and negative-sequence elements for the feeder under ground fault condition. What is of interest in this case is the zero-sequence impedance network. Without EVSE, zero-sequence path is provided by the substation $\Delta - Yg$ transformer. The addition of EVSE with internal $Yg-\Delta$ transformer can potentially add the additional zero-sequence path. In this case, electric utility's 12.47kV-480V $Yg-Yg$ primary transformer (which is typical transformer used on the distribution primary system) and EVSE internal $Yg-\Delta$ 480V transformer are connected in series. As seen from the figure, the equivalent zero-sequence circuit for $Yg-Yg$ transformer is the impedance of this transformer Z_T between its primary and secondary side, while the equivalent zero-sequence circuit for $Yg-\Delta$ transformer is the impedance of this transformer Z_T between its primary and neutral N_0. Equivalent positive-, negative-, and zero-sequence circuits for LG fault are shown on Fig. 7. As seen from this figure, the addition of internal $Yg-\Delta$ transformer within the electric vehicle charging station creates the additional zero-sequence path, that allows the flow of portion of the feeder unbalance current in normal operating mode, and fault current during the ground faults.

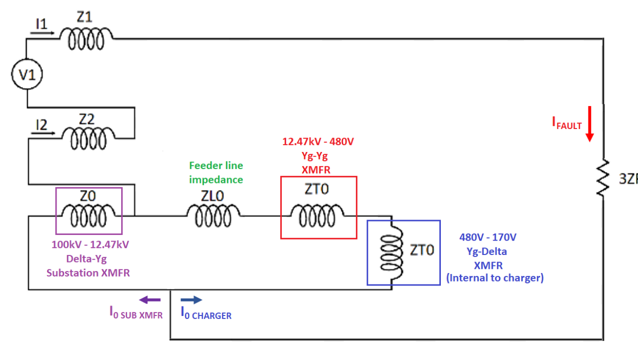

Fig. 7: Equivalent zero-sequence circuit for LG feeder fault with single charging station on the feeder

Electric utility's 12.47kV distribution feeder shown on Fig. 3 was converter into MATLAB/Simulink software as shown on Fig. 8.

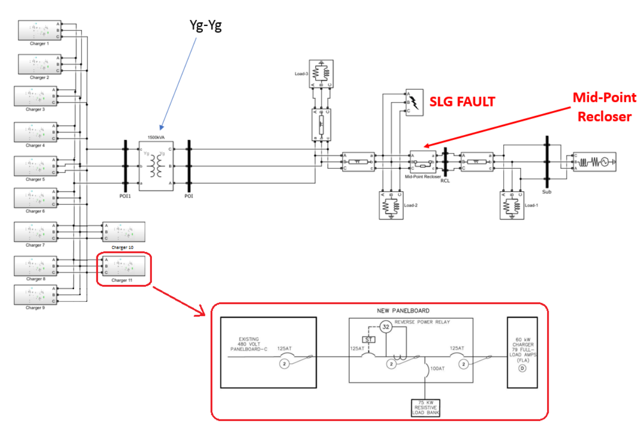

Fig. 8: Line-to-ground fault on the feeder

SLG fault was placed on the feeder primary, downstream from mid-point recloser. EVSE with 11 chargers was installed 4.5 miles from the substation, and EVSE was modelled as shown on Fig. 1. Additionally, 480V distribution panel was modelled as shown on the bottom of the Fig. 8. Fault current, as measured by the mid-point recloser is shown on Fig. 9.

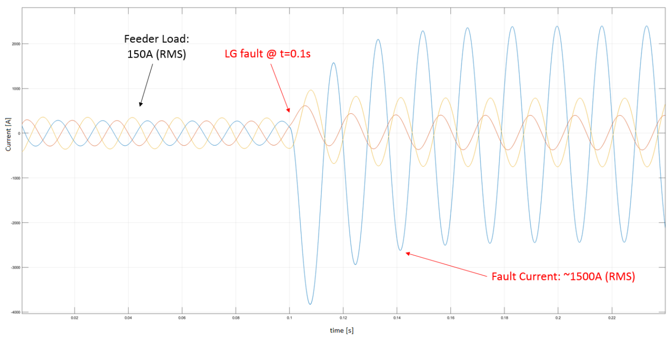

Fig. 9: Mid-point recloser current during line-to-ground fault on the feeder

Note that in this case, relay protection has been turned-off in order to see the maximum level of fault current. As seen from the Fig. 9, feeder load current of 150A (pre-fault) increases to approximately 1500A during the fault. At the same time, measured current between the ground and neutral of the EVSE internal $\Delta - Yg$ transformer is shown on Fig. 10, and it reaches approximately 1900A (note that this is 480V bus, so the ground fault current in this case will be higher).

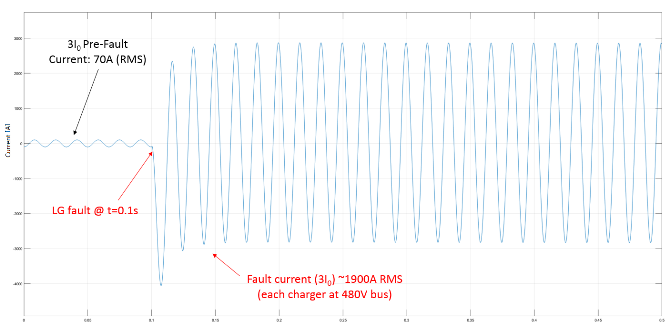

Fig. 10: Charger neutral current ($3I_0$) during line-to-ground fault on the feeder - no protection

Following, breaker curve was implemented within 125AT 480V breaker(MCCB Solid State Trip Unit), which protects the EVSE, and, as seen from the Fig. 11, this breaker trips within 80ms (5 cycles). In the study, 125AT breakers tripped on all 11 EVSE, and total reduction in fault current seen by the upstream recloser was 23% at the onset of the fault.

So, in this case, there are several negative consequences of installing internal $Yg - \Delta$ EVSE transformer.

1) Any feeder ground fault will cause every EVSE breaker protection to trip, which in turn would require someone to manually reset these breaker when the fault has been cleared, and
2) Upstream breaker/recloser ground protection can be de-sensitized to the point where the breaker/recloser does not immediately operate.
3) Fault current exposure causes magnetostrictive core vibration, winding thermal heating and stress during feeder faults. Repeated exposure of the EVSE transformer to

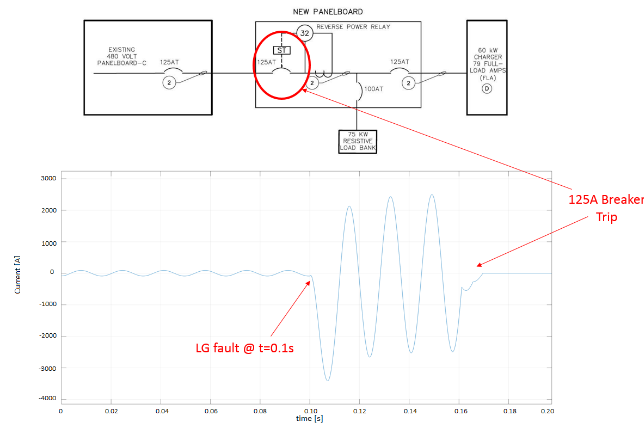

Fig. 11: Charger neutral current ($3I_0$) during line-to-ground fault on the feeder with protection

feeder ground faults will likely result in pre-mature failure of the transformer.
4) The installation of this type of EVSE transformer also increases the fault current duty and interrupting rating required for customer equipment on the 480V secondary. This may require retrofit or replacement of equipment that previously was acceptable without the EVSE charger present.
5) If a single charger is used, the customer would not be able to distinguish a feeder fault from a fault in the charger. Loss of the ability to fault locate is a major safety concern and could result in a technician closing a breaker onto a already faulty charger.

IV. Solutions

There are several potential solutions that could mitigate the challenges outlined above. However, each solution has its own pros and cons.

1) Solution #1: Install $\Delta - Yg$ Point of Interconnection (POI) transformer (instead of Yg-Yg);
2) Solution #2: Float the neutral of Yg-Yg POI transformer;
3) Solution #3: Install $\Delta - Yg$ low-frequency transformer on customer (480V) side,
4) Solution #4: Install $Yg - Y$ low-frequency transformer within EVSE, and
5) Solution #5: Install $Y - \Delta$ low-frequency transformer within EVSE

A. Solution #1: Install $\Delta - Yg$ Point of Interconnection (POI) transformer (instead of Yg-Yg)

This solution is shown on Fig. 12. The main advantages of this solution are:

1) Blocking of zero-sequence path,
2) No ground current contribution for feeder faults by the chargers.
3) No desensitization of ground protection at the substation recloser.

The main disadvantages of this solution are:

1) Causes increase in ground fault current on customer side,

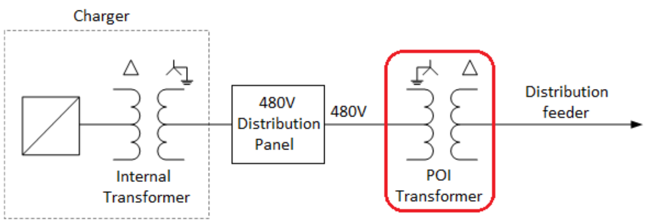

Fig. 12: Solution 1: Installing $\Delta - Yg$ POI transformer

2) Blown single-phase fuses induces large ground currents in charger's internal $Yg - \Delta$ transformer,
3) Low-side ground fault (51TN) would be required to protect the secondary winding,
4) Ground current division between the EVSE transformer and POI transformer for ground faults,
5) Increased fault duty & Arc-Flash hazard exposure for single-phase faults,
6) Increased through-fault stress,
7) Ferroresonance concerns depending on underground (UG) cable/capacitance (such as upstream capacitor banks) of circuit during single-phase switching of re-closer.
8) Internal faults within the Δ winding will cause two fuses to operate. This causes extreme overvoltages on the customer equipment connected to the LS bus.

Two main concerns with this type of interconnection transformer are transformer internal fault and open conductor faults.

a) POI Transformer Internal Faults: It is worth noting that one of the simulation cases that presents a major problem for the $\Delta - Yg$ POI transformer solution is internal transformer failures. Although this case is not common, simulations show that this case is not favorable for this transformer configuration. If an internal transformer failure does occur, there is a possibility that the charger will not detect the fault. A 5Ω turn-to-ground fault was simulated at 50% of the winding between A and B phases on the primary. This represents the simplest and also worst case. Both the A and B phase fuses operate to clear the internal fault, resulting in a single-phased Delta connection. The fault current was approximately 300A, and resulting in a clearing time of around 3 seconds using a 80K fuse link. During the fault, the voltage observed by the charger changes by less than 0.1p.u., which is highly unlikely to trip the charger. Using undervoltage settings of 0.88p.u., the charger did not trip off during the fault. After the high-side fuses blew, the C-Phase of the utility was still connected and the chargers began feeding the internal transformer failure. This resulted in a 1.5p.u. LG overvoltage at the customer load. After the observed overvoltage condition, the charger unit tripped offline. This is shown in Figure 13. This directly implies that the three-pole operating device (such as a breaker or recloser) is needed on the high-voltage side, if this transformer configuration is used. However, this may not always be practical or economical.

b) Open Conductor Faults: When open conductor fault occurs, one or two phases that open, are generally the result of switching or melting fuses due to the circuit overload.

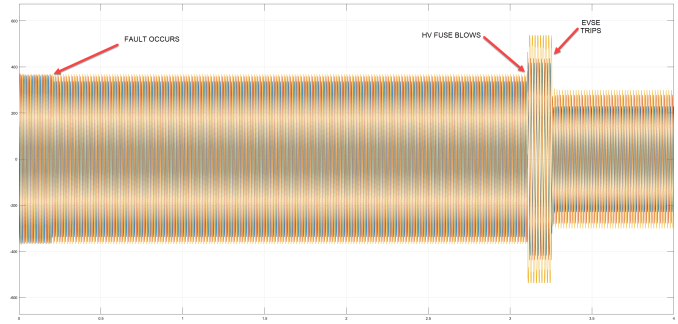

Fig. 13: Internal POI Transformer Failure(Fault in HV winding)

Although not a common occurrence, there have been many instances of in-line fuses that have melted due to circuit loading, thereby causing an open conductor fault.

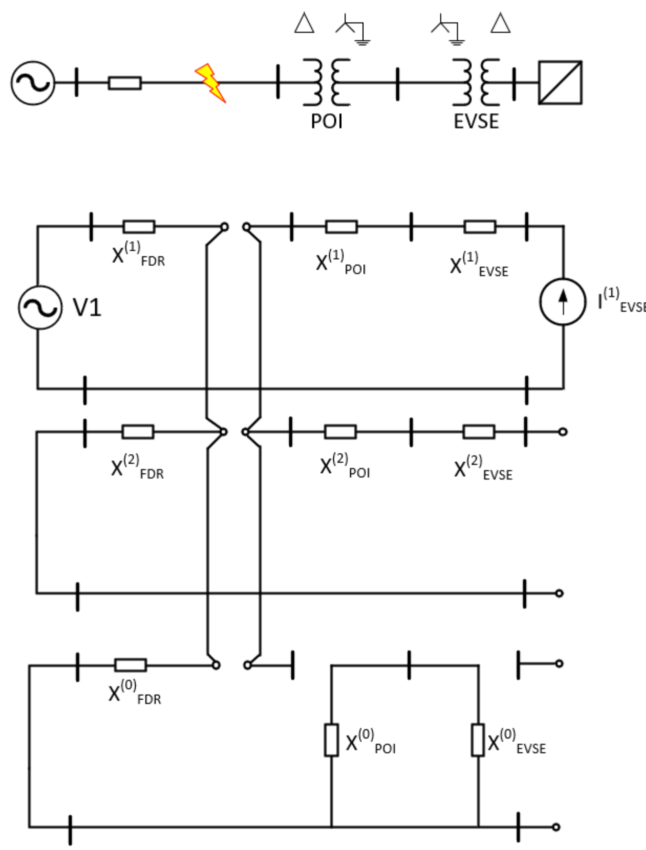

Fig. 14: Single Phase Open Conductor Fault at HV Winding(Delta-Yg POI)

Analyzing a open conductor illustrates some of the protection challenges with choosing a specific transformer. Protection techniques are explicitly dependent on the EVSE and POI transformer configuration. Figure 14 shows the symmetrical components representation of a single phase open condition in the modelled feeder, with the EVSE in a discharging state represented by an ideal positive sequence current source. Notice that the POI transformer is $\Delta - Yg$ and the EVSE internal transformer is $Yg - \Delta$.

During a open conductor fault in Figure 14 it becomes apparent that the EVSE is open-circuited in the positive sequence network. This will cause a large positive sequence voltage to develop at the 480V bus and can damage the EVSE or customer equipment. Therefore, if this scheme is used, the protection engineer must pay particular attention to overvoltage protection settings on the 480V bus. Although customer loading is not shown on the diagram, inserting an impedance in the sequence networks representing load decreases overvoltage concerns for heavily loaded circuits. For lightly loaded networks, an aggressive overvoltage scheme would be required to protect customer loads and lightning arrestors.

Changing the POI transformer to $Yg - Yg$, the symmetrical component diagram show in Figure 15 shows that large ground current will flow through the EVSE internal transformer for an open conductor fault. This implies that special consideration must be given to ground time overcurrent protection to protect the EVSE transformer from damage during this condition. Overvoltage protection is less of an concern due to the discharge path through the zero sequence network. During simulations, a single open conductor resulted in a ground current of over 500A measured at each charger neutral.

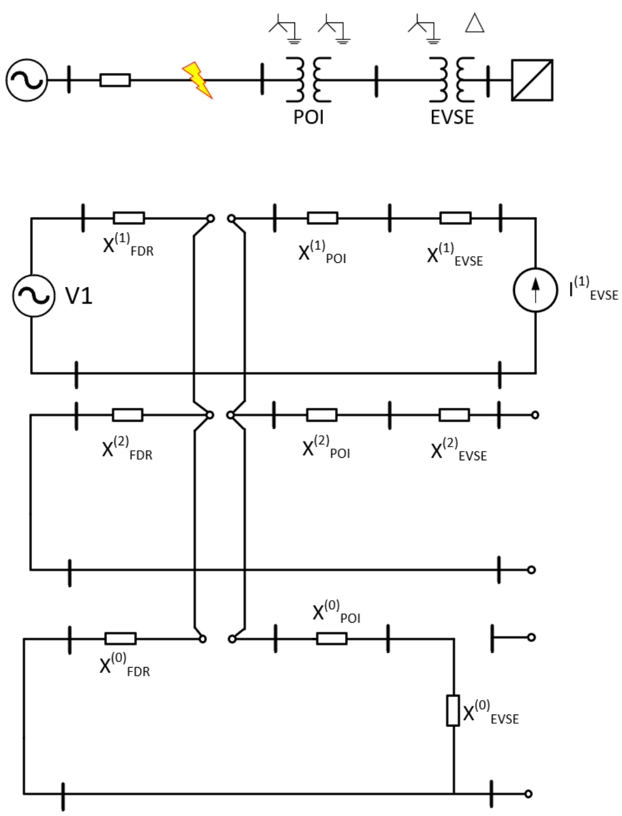

Fig. 15: Single Phase Open Conductor Fault at HV Winding(Yg-Yg POI)

B. Solution #2: Float the neutral of Yg-Yg POI transformer

This solution is shown on Fig. 16

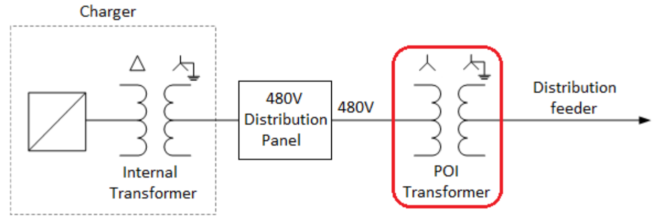

Fig. 16: Solution 2: Installing $Yg - Y$ POI transformer

The main advantages of this solution are:

1) Blocking of zero-sequence path,
2) No ground current contribution for feeder faults by the chargers,
3) No desensitization of ground protection at the substation recloser.

The main disadvantages of this solution are:

1) Loss of effective ground on the secondary for customer loads,
2) Ground fault current will be directly dependent on the internal Yg-Delta charger transformer. Simultaneous tripping of the 125A breaker will cause loss of effective ground on the 480V network. This inherently causes a race condition between the POI transformer fusing and EVSE charger 125A breaker. In the event that the 125A breaker operates before the HV fusing, this will cause a loss of effective ground(this case is presented later).
3) Potential for LS arrestor failure, overvoltages and severe voltage imbalance when the are chargers offline(or during ground fault 125A CB tripping).

This solution was also simulated with ground fault implemented on 480V section as shown on Fig. 17.

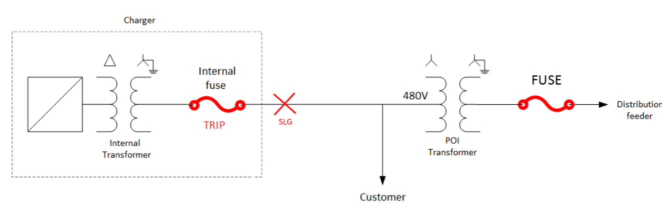

Fig. 17: Solution 2: 480V line-to-ground fault with $Yg - Y$ POI transformer

In this case, the 125A EVSE circuit breaker(s) clear the fault on 480V side as shown on Fig. 18

However, loss of effective grounding in this case causes the severe overvoltage that can potentially damage the equipment and loads as shown on Fig. 19. In this case, the internal fuse within the EVSE fails to clear the fault, and if the ground fault is still present, internal EVSE protection (undervoltage/overvoltage (27/59)) can potentially clear the fault.

Note that this type of transformer configuration ($Yg - Y$) is traditionally used with large DERs, which do not have internal transformers. The floating side of this transformer is used as an input to the inverter, which uses 3-phase, ungrounded power supply.

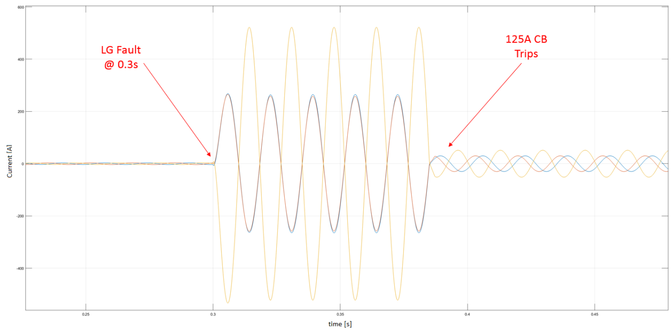

Fig. 18: Solution 2: 125A circuit breaker trips for 480V line-to-ground fault

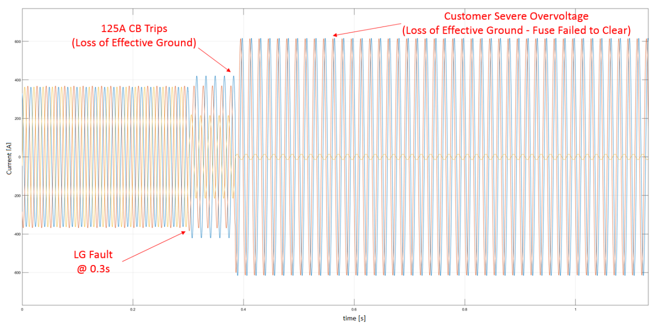

Fig. 19: Solution 2: Charger overvoltage after 125A circuit breaker trip for 480V line-to-ground fault

C. Install $\Delta - Yg$ low-frequency isolation transformer on customer (480V) side

This solution is shown on Fig. 20.

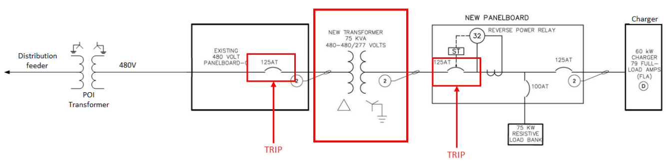

Fig. 20: Solution 3: Installing $\Delta - Yg$ 480V low-frequency transformer

The main advantages of this solution are:

1) Blocking of zero-sequence path,
2) No ground current contribution for feeder faults by the chargers,
3) No desensitization of ground protection at the substation recloser.

The main disadvantages of this solution are:

1) Increased complexity of protection of low-frequency transformer (detailed PC Study would be required),
2) Ground fault current division between charger and low-frequency transformer,
3) Challenges with fault location,
4) Increased GF duty for ground faults between charger and low-frequency transformer,
5) Inability disinguish a ground fault between the isolation transformer/EVSE and a faulty charger. Loss of the ability to fault locate could be a safety concern.

D. Install $Yg - Y$ low-frequency transformer within EVSE

This solution is probably the most optimal solution from the protection standpoint, because it resolves most of the challenges outlined in this paper. As seen from Fig. 21, Yg side would still be connected to 480V bus, and secondary side would still provide 3-phase ungrounded input to the power electronics section of the EVSE. The benefit of this solution is open circuit for zero-sequence current path, so in grid-connected mode, there is no current flowing between the neutral and ground of Yg side of this transformer. Similarly, there is no fault current flowing between the ground and neutral of the Yg side of this transformer during the ground fault current conditions. This transformer configuration resolves two of the major challenges identified above: upstream relay will still measure full ground fault current (instead of seeing this fault current lowered by 23%, and also, 480V breakers in the distribution panel feeding the EVSE would not trip for the feeder ground fault.

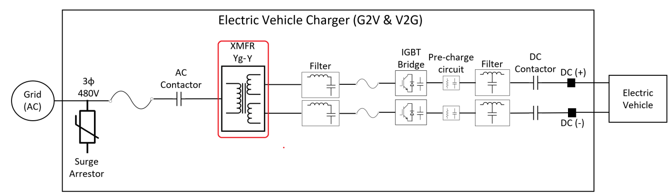

Fig. 21: Solution 3: Installing $Yg - Y$ internal low-frequency transformer within EVSE

This solution would need to be implemented by the EVSE vendor and it would most likely require UL 1741 and possibly some other certifications, which would require certain level of financial investment.

E. Install $Y - \Delta$ internal low-frequency transformer within EVSE

This solution is also an option, because it resolves most of the challenges outlined in this paper, given that this transformer configuration has zero-sequence network as an open circuit for both Y and Δ sides of the transformer. As seen from Fig. 21, Yg side would still be connected to 480V bus, and secondary side would still provide 3-phase ungrounded input to the power electronics section of the EVSE. The benefit of this solution is open circuit for zero-sequence current path, so in grid-connected mode, there is no current flowing between the neutral and ground of Yg side of this transformer. Similarly, there is no fault current flowing between the ground and neutral of the Yg side of this transformer during the ground fault current conditions. This transformer configurations resolves two of the major challenges identified above: upstream relay will measure full ground fault current (instead of seeing this fault current lower by 23%, and also, 480V breakers in the distribution panel feeding the EVSE would not trip for the feeder ground fault.

V. Conclusion

As a conclusion, $Yg - \Delta$ transformer internal to the electric vehicle charger acts as a ground source, which presents couple

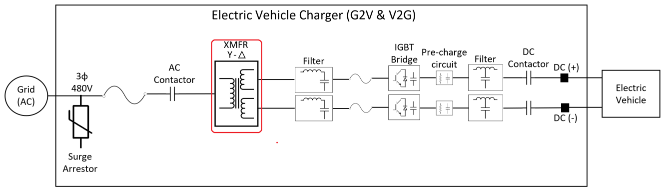

Fig. 22: Solution 3: Installing $Y - \Delta$ internal low-frequency transformer EVSE

of challenges. First, in grid connected mode, this transformer carries certain portion of feeder unbalance current, which has a negative impact on its useful lifetime, because it continuously causes the transformer to overheat. Second, during feeder ground fault conditions, this transformer provides the additional zero-sequence path, which causes certain portion of fault current to flow through this transformer, which is, by design, not sized for this condition. This creates couple of challenges: premature failure of this transformer and also reduction of the ground fault current seen by upstream protective device (in our case, this reduction was recorded to be 23% for a system of 11 charging station totaling 660kVA of capacity). For that reason, five solutions were proposed to resolve this problem, each of which has its pros and cons.

VI. Acknowledgement

The authors would like to acknowledge the contribution to the article by Michael Rowand.

References