

Modelling and Testing of Temporary Protective Grounds Cable Systems for High Fault Current Applications

Anil PODA, Josh PERKEL, Thomas LANCASTER, Nigel HAMPTON; GATECH/NEETRAC, (USA),
Anil.poda@neetrac.gatech.edu, Joshua.perkel@neetrac.gatech.edu, Thomas.lancaster@neetrac.gatech.edu,
Nigel.hampton@neetrac.gatech.edu

ABSTRACT

Temporary protective grounds are cable systems (cables, connectors and special terminating clamps) that are used to provide adequate protection to line workers while working on the de-energized electrical power systems that can accidentally become energized. In typical applications a single cable system TPG is used, however, there is a growing number of high fault current substations where the capacity of a single TPG is insufficient, yet the critical safety application of a TPG cable system is required.

Consequently installing more than one TPG for high fault current applications is a widely accepted practice in the electric utility industry. The extreme electro-mechanical forces present under high fault current conditions can cause failures of TPG assemblies below their cumulative single rating. Unlike thermal energy, the electro-mechanical forces on individual TPGs do not reduce in the same proportion as the current. The laboratory tests were performed on three parallel TPG sets with different spacing distances at 80 kA in a similar method to ASTM F855 requirements. The results strongly indicate that the spacing between the parallel TPGs should be installed as close as possible to each other to reduce the likelihood of failure due to electro-mechanical forces during the high fault current conditions.

This poster will provide details of the testing to verify the critical design parameters and the circuit modeling of the TPG cable systems in a multi parallel arrangement. The value of the modeling, whereby the experience can be extended to many different cases as shown with selected case studies.

KEYWORDS

Grounding, electrical safety, sizing TPG sets.

INTRODUCTION

Temporary protective grounds (TPGs) are intended to be installed on de-energized lines and equipment to protect workers from death or injury in case of accidental energization of the line during installation or maintenance work. Application of TPGs on de-energized lines and bus work creates a short circuit path, which limits the voltage between the phase and neutral/shield conductors, and carries the fault currents to neutral/shield conductors at the work site [1]-[3]. This allows any upstream protection to operate. TPG assemblies consist of clamps, ferrules, and interconnecting cable with a jacket [3].

In grounding applications, there are certain situations where a single temporary grounding cable does not have the required current carrying rating. In this situation, identical ground cables may be connected in parallel to achieve the necessary rating. In a typical application

location, such as transmission lines and substations at some distance from generating station, an accidental switch closing can initiate a highly asymmetrical fault current due to sub-transient, transient, steady state ac components, and the dc offset components. The application of multiple TPGs reduces the size requirements for any individual TPG assembly [5], [7]. ASTM F855 recommends that the users seeking applications of multiple assemblies at high X/R locations should perform their own tests to verify the performance of the assembly. It is unclear, however, how much current a parallel configuration can successfully carry as compared to a single TPG configuration.

SELECTION OF TEMPORARY PROTECTIVE GROUNDS

ASTM F855 recommends performing internal testing when there is a need to use multiple TPGs on a single phase conductor. This standard also provides ratings for different individual TPG configurations up to 68 kA. However, there are locations with available fault currents well in excess of 68 kA, sometimes even above 80 kA. In addition to the available fault current, there are physical size limits to the conductors themselves as line personnel must be able to maneuver and attach the cables to the appropriate structure. Therefore, it is also possible that a utility may decide to use multiple small conductor TPGs instead of a single large TPG to carry the same amount of high fault current.

The most commonly used sizes and designs of TPGs for different fault currents were identified based on a survey conducted among 40 utility and manufacturing companies located in North America (representing around 70 million utility customers). A 6.1 m (20 ft) long 4/0 conductor design was selected for a three parallel TPG configuration that was ultimately tested at 80 kA. Other parts of the TPG design were also chosen from the survey, as specified in Table I. All the components required to build the TPGs were assembled by the manufacturer and were then tested at the Nicholas J. Conrad High Power Laboratory (NJCL) located in Chicago, IL, USA.

Table I: TPG Component Specification

Component	4/0 Specification
Cable Size	4/0 AWG
Ferrule	Threaded with shroud
Strain Relief	Yes
Top Clamp	Grade 5 C-Clamp
Bottom Clamp	Grade 5 C-Clamp
Cable Length	6.1 m (20 ft)
Install torque	Manufacturer specified

EXPERIMENTAL DETAILS

Test Setup and Procedure

The testing was performed using an 850 MW short circuit generator test set that can produce fault currents up to 100 kA RMS symmetrical. Three new 4/0 TPG assemblies were installed in parallel between two solid aluminum busses with equal spacing between each TPG assembly as shown.

Table I from ASTM F855 defines the rating for symmetrical faults which are classified as having an X/R ratio of less than or equal to 1.8 [4]. Table II of ASTM F855 defines the ratings for asymmetric faults with an X/R = 30. This leads to a first cycle peak of 2.69 times the RMS current.

Most standards recommend de-rating the fault current carrying ability of TPGs at least by 10% when an application involves connecting them in parallel. This recommendation is intended to account for the unequal current distribution between TPGs and the additional forces that are produced. In the presence of high magnitude asymmetric currents, the electromechanical forces are extremely high as they are produced by the interaction between the the instantaneous current on each TPG and may require further de-rating.

Based on these de-rating recommendations, the presented work was focused on installing three 4/0 TPGs side by side and applying an asymmetric current of 80 kA ($1.7 I_{rated}$) RMS for 15 cycles (each individual 4/0 TPG is rated for a 47 kA RMS fault current for 15 cycles according to ASTM) with X/R ratio of 30 [5]. The three TPGs were connected in parallel between the top input bus and the bottom return bus as shown in Figure 1.

The test structures were assembled such that the vertical separation between the input and return bus was 3.05 m (10 ft) and the horizontal separation between the phase conductors was 1.83 m (6 ft). The return bus was raised to a height such that when the TPGs were installed, they would hang freely and not touch the floor. Fault current was applied from the top input bus to the bottom return bus through the parallel TPGs for 15 cycles. All of the faults applied had an X/R of as close to 30 as could be supplied by the high power laboratory. Examples of the measured fault current through return bus when the three TPGs were placed at a center to center clamp spacing of 0.31 meters (12 in) and 0.09 m (3.5 in) (which was the smallest spacing possible) are shown in Figure 2 and Figure 3, respectively.

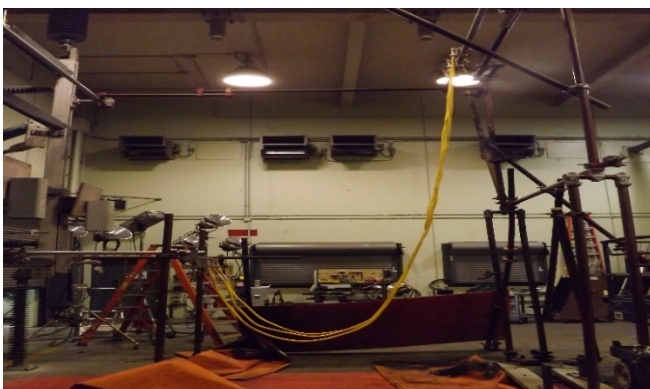


Figure 1: Test Setup for three parallel TPGs configuration

Test Results

For each test configuration, four replicates were tested to verify the repeatability of the results. The three parallel TPGs were tested at 80 kA at three spacing distances between the TPGs (0.305 m, 0.152 m, and 0.09 m (12 in, 6 in, and 3.5 in)). The test results are placed in Table II.

Table II: High Fault Current Test (80 kA) results of Three 4/0 Parallel TPGs at Different Spacing Distances

Cable Size	TPGs [#]	Clamp Spacing Meter (inch)	1.7 I_{rated} (80 kA)	
			Tested	Survived
4/0 $I_{rated} = 47$ kA	3	0.31 (12)	4 Sets	0
		0.15 (6)	4 Sets	1
		0.09 (3.5) (smallest possible for clamp design)	4 Sets	4

The results for each test were recorded and an example of the waveforms and high speed videos recorded are shown in Figure 2 and Figure 3 for the spacing distances of 0.305 meters and 0.09 m (12 in and 3.5 in) apart, respectively. When the three TPGs were placed 0.31 m (12 in) apart, all four replicates failed to withstand the fault current. When the three TPG sets were tested at 0.15 m (6 in), only one set survived. All four replicates survived when the three TPG sets were installed as close as possible (0.09 m (3.5 in) for the design selected for this work).



Figure 2: Example Waveform and High Speed Video for 0.305 m (12 in) Spacing

Failure Modes of Parallel TPGs Under High Fault Currents

From the test results in Table II, it is evident that the failure rate of the parallel TPGs is higher when they are installed with larger spacing between the clamps. If the spacing between the clamps increases, the current sharing becomes more unequal with the source side assembly carrying more current and the forces on the clamps increasing. This can cause either of the two primary modes of failure for TPG in a fault condition which are mechanical and thermal failures.



Figure 3: Example Waveform and High Speed Video for 0.089 m (3.5 in) Spacing

Thermal Failure Phenomenon on Parallel TPGs

Thermal failures are due to the clamp, ferrule, or conductor of the TPG not being able to carry the fault current without overheating. These are characterized by the clamp/ferrule/conductor melting and detaching from the structure such that the TPG is no longer carrying the fault current. These types of failures occur during the final cycles of the fault after the TPG has had time to heat to its melting point. Few of the tests conducted here experienced this failure mode.

The large initial current peaks associated with high X/R ratios have significant impact on the thermal rating of a TPG particularly for short duration fault currents. This is because the thermal energy in a TPG is proportional to $i_f(t)^2$ as represented by following relationship [4, 5]:

$$\Delta Q = K \times i_f(t)^2 \times r(t) \times \Delta t \quad [1]$$

Where,

ΔQ = Heat generated during each interval Δt , Calories

Δt = Assumed duration of each interval, seconds

K = A constant to convert from Joule to Calories (0.239 Cal/J or 4.184 J/Cal)

$i_f(t)$ = Instantaneous asymmetrical fault current at any instant t (seconds), amperes

$r(t)$ = Resistance of a 0.31 m (1 ft) long grounding cable in Ohms.

Analyses on Electromechanical Forces on Parallel TPGs

Slowly decaying high amplitude current peaks have significant influence on the instantaneous mechanical stresses on a TPG assembly. Extreme electromechanical forces present under high fault conditions can break the assembly loose from the attachment point or break the clamp, leaving the worker without protection. Unlike thermal stresses, the mechanical stresses on a TPG are not only proportional to the TPG's own current but also proportional to the currents flowing in other circuit elements such as phase conductors, shield/neutral conductors and

associated earth paths, and other nearby TPGs in the case of parallel assemblies. These high forces cause the mechanical failures which occur during the first one to two cycles of the fault when the currents and electromechanical forces are highest.

The de-rating of the TPGs is mainly due to the complex interaction of forces acting on the TPGs when they are installed in parallel. As more TPGs are added to the assembly, the force distribution becomes more complex as each TPG exerts a force on every other TPG and at high currents, they can be large and uneven across the assembly. These uneven forces lead to the highest force occurring on the TPG closest to the source of the fault which may cause it to break first. Although the net influence of these elements on the subject TPG is extremely difficult to determine theoretically, a graphical basis is demonstrated in Figure 4 through Figure 6 for a three TPG assembly. Figure 4 shows the forces acting on the TPG closest to the source of the fault. F_{1Loop} is the loop force from the current flow that pushes the conductors in the loop away from the fault source. This force occurs whether there are multiple TPGs or just one TPG present. F_{12} and F_{13} are the additional forces on the first TPG caused by the second and third TPGs, respectively. Since the second and third TPGs are to the right of the first TPG, both of the forces due to these TPGs are in the same direction – away from the source and are thus additive.

Figure 5 shows the forces acting on the second TPG in the assembly. Similar to the first TPG, there are three forces present. These forces are the loop force that pushes the conductors away from each other, and the two forces due to the other TPGs in the assembly. For the second TPG, the loop force F_{2Loop} is still going to the right, but now there are TPGs on either side of the second TPG. This makes F_{21} and F_{23} act in opposite directions from each other with only one going in the same direction as the loop force. This leads to a lower net force than is seen by the first TPG.

Figure 6 shows the forces acting on the third TPG in the assembly. In this case, the loop force F_{3Loop} is still going to the right, but now the two forces due to the other TPGs are going to the left since both of the other TPGs are to the left of the third TPG. Thus this TPG sees the lowest net force.

As fault currents increase, the forces also increase which may ultimately exceed the mechanical strength of the first TPG clamp. This can cause a mechanical failure of the clamp even though the thermal rating of the conductor and clamp were never reached. This problem can be worsen if the current return paths for each TPG are not equal in impedance. When there are unequal impedance paths, the current will take the path of least impedance which can result in the current being forced down alternative paths which may or may not exacerbate the stress on each TPG. This was observed during the testing performed for this work.

Figure 7 shows the forces on the TPGs observed from the laboratory testing where the three TPG cables were pushed together due to the electromechanical forces. The test condition was performed using a single return bus to have a matched impedance path back to the source so that the current split was due to the TPG differences only. The test results indicate that the currents were close to balance as evidenced by the positions of the cables during the fault current test (i.e. they came together in the middle).

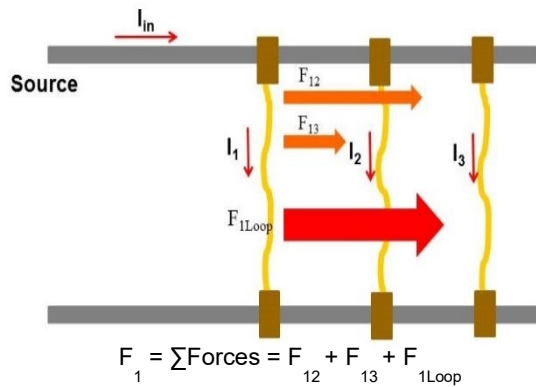


Figure 4: Forces on TPG 1 (closer to Source)

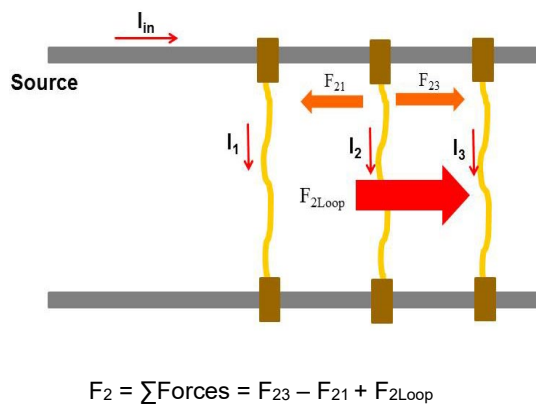


Figure 5: Forces on TPG 2

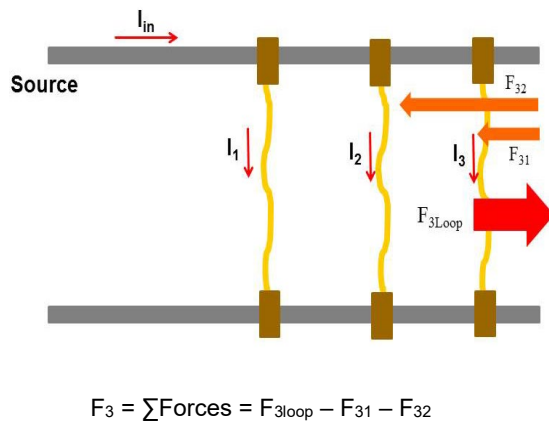


Figure 6: Forces on TPG 3

This effect is also demonstrated by the improved performance of the assemblies as the spacing between TPGs is reduced. In the testing performed, the failures of the assemblies followed a similar pattern across all tests. The first failure in the assembly was a mechanical failure of the first clamp due to the initial whipping action of the cable. When the current was applied, the magnetic field caused the cables to rapidly come together which produces a sudden force on the clamp. Once the first clamp released, the second clamp saw a rapid increase of the force applied as the current redistributed and the second clamp suffered a mechanical failure due to the whipping action of the cable. By this time, the third clamp was already in its bent position and the clamp did not see the whipping action of the cable and did not suffer a mechanical failure.

As the spacing between TPGs decreases, the amount of bending of the clamp when the TPGs come together is reduced since the cable must move a smaller horizontal distance. This reduced bending decreases the likelihood of a mechanical failure of the first clamp. When the first clamp survived the initial whipping force of the cable, the assembly survived since the current through each TPG was much lower than its thermal rating. Restraining the TPGs has a similar effect in that the cable cannot move as far and the force of the cable is limited by the restraint. If the initial force on the clamp can be reduced so that the clamp can survive the initial whipping action by the cable, the assembly has a much higher likelihood of surviving. However, care must be exercised if using restraints to increase current carrying ability as the user must be sure of where the fault will come from in order to properly position the restraint.

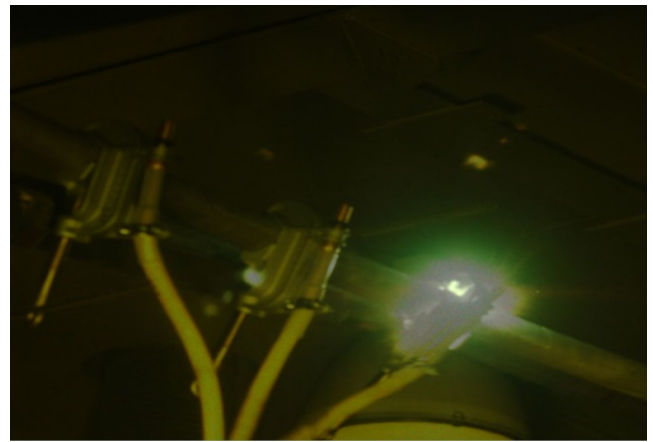


Figure 7: Electromechanical failure of a TPG on source side at 0.305 m (12 in) spacing

SIMULATION MODEL DESIGN AND ANALYSES

Simulation Model Design

A simulation model was designed in a MATLAB® Simulink® platform using the test parameters used in the high power laboratory such as voltage source, input bus structure, three TPGs, and measurement components etc. The simulation model appears in Figure 9. The input bus consists of a resistor and inductor in series and is used to create the desired X/R ratio. The incoming fault current along with the individual currents in each TPG are simulated and recorded.

The TPGs consist of a resistance and a mutual inductance module that simulates mutual and self-inductances for the parallel TPGs. Due to the difficulty in measuring the inductances of the TPGs in their testing configuration, calculations were made to determine the estimated inductance of the setup. The self-partial inductances were calculated using Equation [2] below [6].

$$L_p = \frac{\mu_0}{2\pi} * l * \left[\ln\left(\frac{2l}{r_w}\right) - \frac{3}{4} \right] \quad [2]$$

Equation [3] calculates the mutual partial inductance [6]. In the formulas, r_w is the radius of the TPG cable and l is the length of the TPGs. All dimensions are in meters. Using this formula, the estimated self-inductance of the 4/0 TPGs with a cable OD of 22.09 mm (0.87 inches) is calculated as 6.78 μH .

The mutual inductances for the TPG arrangements were calculated for each configuration using Equation [3] below [6]. Note that this equation assumes the currents will be in the same direction.

$$M_p = \frac{\mu_0}{2\pi} * l * \left[\ln \left(\frac{1}{d} + \sqrt{1 + \frac{l^2}{d^2}} \right) - \sqrt{1 + \frac{d^2}{l^2}} + \frac{d}{l} \right] \quad [3]$$

In this formula, d is the center to center distance between the conductors and l is the length of the TPG in meters. For each setup design, the computer model calculates what the mutual inductances are and puts the values into the model.

An example output of the simulation is shown in Figure 8. The outcome of the simulation model plot shows the incoming fault current as the input current and the currents through each TPG with TPG 1 being closest to the source and TPG 3 being farthest from the source.

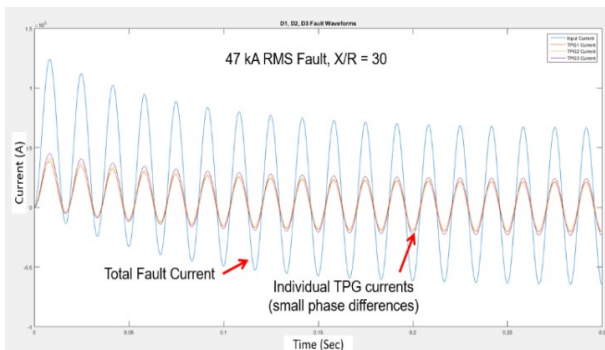


Figure 8: Example Simulation Output Waveform

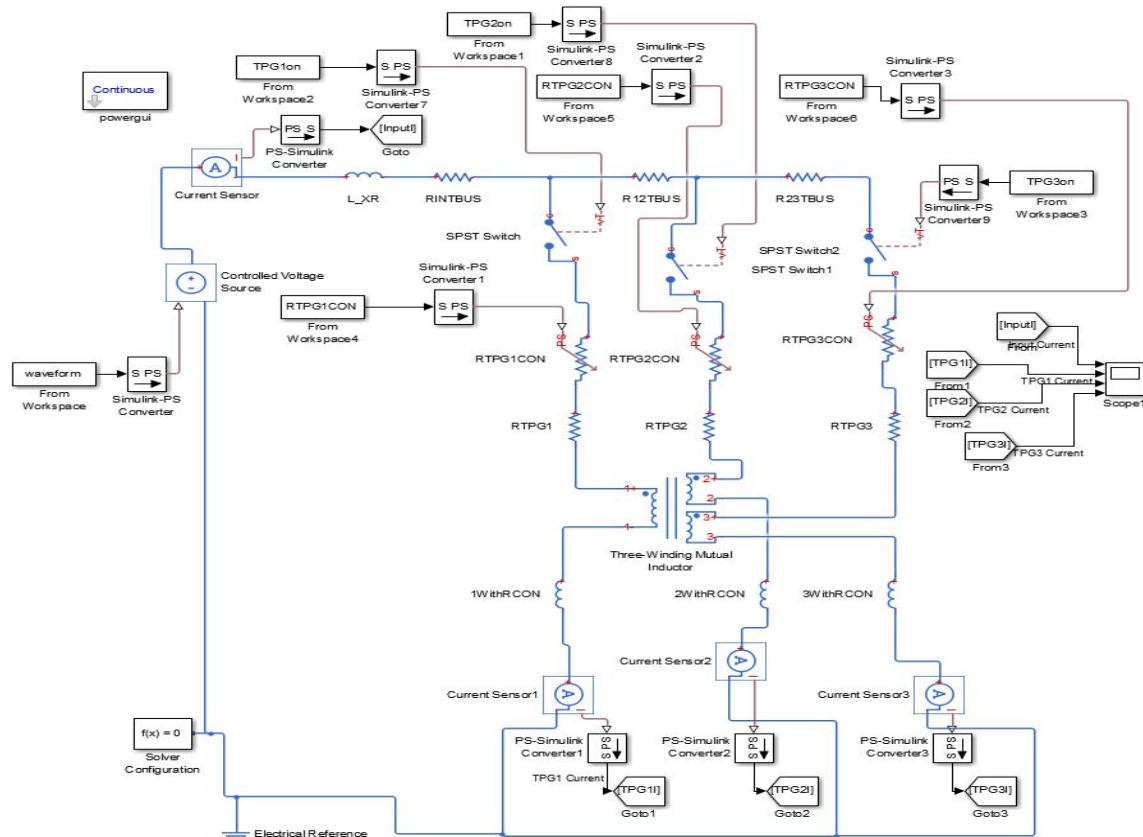


Figure 9: MATLAB Simulink simulation model

Validation of the Simulation Model

In order to verify the model, actual test data was compared to Monte Carlo simulations run using the model. The Monte Carlo simulations consisted of 10,000 iterations of the simulation with the resistance of the TPGs being chosen at random from the distribution, of measured TPG resistances.

The simulated peak currents tracked closely with the measured current peaks from the laboratory test results as shown in Figure 10. The error percentage between the simulation results and the laboratory test results are less than 0.01%. These results validated the model and showed that it could be used to predict the magnitudes and waveforms of the current splits for three TPGs in parallel.

Application of Model to Other Scenarios

The simulation model was applied to other configurations to see what the effects of changing the parameters of the model. In the simulations shown previously, all of the TPG resistances were selected from the same 4/0 AWG TPG sample resistance distribution (1208.04 $\mu\Omega$ mean). This was done to simulate using all new TPGs as tested in the laboratory. The resistances could be varied to see what the effects of aged TPGs with higher resistances would be on the current splits. Using the model, this effect was examined as a proof of concept. The resistances of the TPGs were modified such that the TPG1 (Maximum allowed TPG resistance according to ASTM F2249 for a 4/0 AWG sample, 1349.59 $\mu\Omega$) of the assembly had the highest resistance.

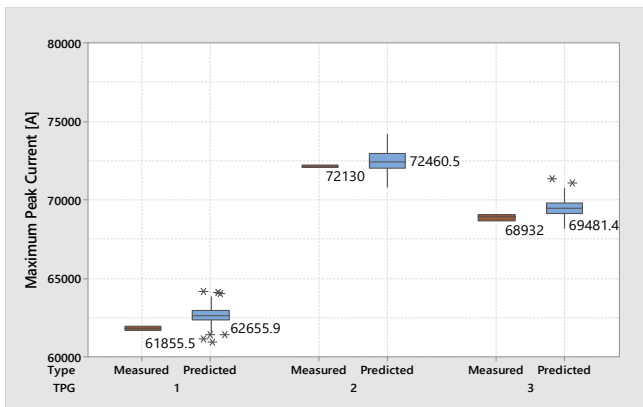
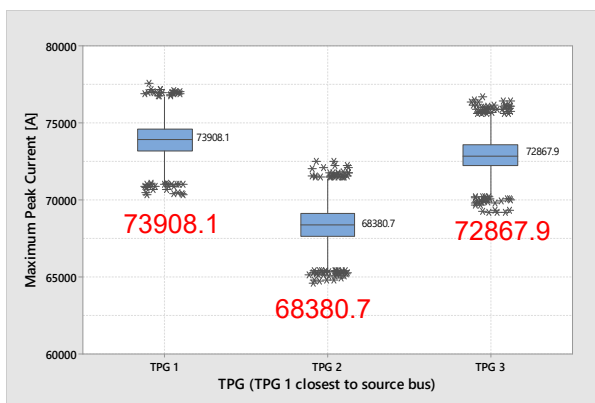
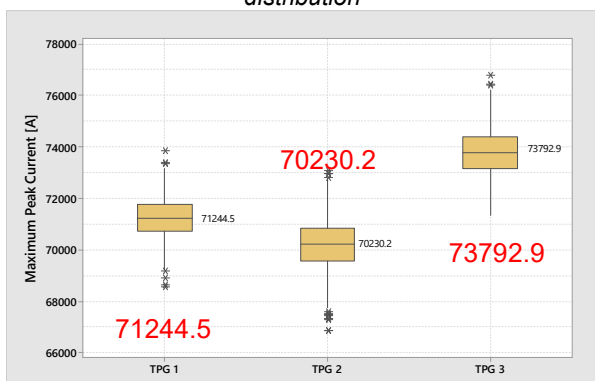


Figure 10: Comparison of simulated peak currents to measured peak currents

A Monte Carlo simulation was performed using these resistance distributions and a 0.305 meter (12 inches) spacing between TPGs for an 80 kA fault with an X/R ratio of 30 [4]. The results of the simulation were plotted for comparison in Figure 11. With the higher resistance cable placed closest to the source in a three TPG configuration, the model predicts that the current amplitude in the farthest TPG (TPG3) to the source will be approximately 1,000 A higher than before.



i. TPG Currents with resistances from new sample distribution



ii. TPG currents when TPG1 resistance is considered as higher while other two TPGs remain new

Figure 11: Comparison of peak current splits for model extension

CONCLUSIONS

Temporary protective grounds are used to provide safe and reliable protection to the linemen working on de-energized power system equipment that could become energized unexpectedly. This paper was focused on explaining the importance of spacing distances between parallel TPGs. The failure mechanisms causing failure of parallel TPGs at higher spacing distances are explained using a three TPG set configuration.

The work presented in this paper demonstrates that, as the spacing between the assemblies increases, the current sharing becomes more unequal and also the net electromechanical forces on the set of TPGs increases. In order to maintain equal current splits between parallel TPGs and to limit the electromechanical failures on parallel TPG sets, the TPGs should be installed side by side with the least possible spacing between the TPGs.

This paper also presents a simulation model to calculate the current split between parallel TPGs in one configuration. Laboratory tests were performed on a parallel 4/0 three-TPG configuration at 80 kA and used to refine and validate the model. The work presented in this paper demonstrates that the current split between TPGs can change drastically because of the change in individual TPG resistances. This model permits users to optimize their laboratory test programs to focus on the design parameters of greatest concern for their parallel TPG configurations.

Acknowledgments

The authors wish to thank NEETRAC members for their sponsorship of this research, and the staff at the NJCL High Power Laboratory for their support performing this work.

REFERENCES

- [1] James R. White and Shahid Jamil, 2016, "Do's and Don'ts of Personal Protective Grounding", IEEE Trans on Industry Applications, Vol.52, No.1, pp. 677-683.
- [2] R. E. Mueller and E. F. Richards, 1989, "Temporary Protective Grounding of Distribution Circuits – Revisit Ten Years Later", the Proceedings of the Twenty-First Annual North American Power Symposium, pp. 270-280.
- [3] U. S. Department of the Interior Bureau of Reclamation Denver, 2005, "Personal Protective Grounding for Electric Power Facilities and Power Lines", Vol. 5-1, Colorado, pp.1-81.
- [4] EPRI, RP2446-1, 1987, "Fusing Research on Personnel Grounding Cables", EPRI EL-5258, Final Report, 164 pages.
- [5] Albert Melikian, 2009, "Calculations of Increase in TPG Resistance due to Asymmetrical Fault Current", A Report Prepared for Southern California Edison, California.
- [6] ASTM International Standard Designation F855 – 17, 2017, "Standard Specifications for Temporary Protective Grounds to Be Used on De-energized Electric Power Lines and Equipment".
- [7] IEEE 1246, 2011, "IEEE Guide for Temporary Protective Grounding Systems Used in Substation".