A Simulation Model to Analyze Current Split Distribution of Multiple Temporary Protective Grounds (TPGs)

Anil B. Poda, C. M. Riley, Josh Perkel, R.N. Hampton, Shashi Patel, and Thomas Lancaster
GATECH / NEETRAC
5351 Kennedy Road, Forest Park, GA 30297, USA

Abstract- **The main purpose of Temporary Protective Grounds (TPGs) is to maximize personnel safety while working on any de-energized power equipment. ASTM F855 specified the required designs for individual TPG configurations. In recent times, installing more than one TPG for high fault current applications is a widely accepted practice. The use of multiple TPGs on a single phase conductor would limit current carrying capability of an individual TPG by splitting the high fault currents among the parallel TPGs. The current split between the parallel TPGs depends on the resistance of the individual TPGs and the spacing present between TPGs. However, performing multiple high fault current test configurations at a laboratory is extremely complex and expensive. A three TPG configuration was designed and tested at 80 KA as per ASTM F855 requirements and the current split measurements were taken on each individual TPG. A simulation model was designed to perform different multiple TPGs configurations and the model was verified by comparing with the laboratory test results. An example test case is discussed using the simulation model where if one of the parallel TPGs has high impedance values and the simulation results indicate that the change in resistance of the TPGs impact the current split distributions adversely.**

Index Terms— **Application of grounds, electrical safety, simulation study, sizing TPG sets, temporary protective grounds (TPGs) and testing TPG sets.**

I. INTRODUCTION

The primary purpose of temporary protective grounds is to provide adequate protection by preventing electrical shock to the field personnel while working on the de-energized overhead lines or equipment that can accidentally become energized. One of the main safety concerns for transmission and distribution systems is for linemen and ground support personnel while performing line or substation maintenance. Application of TPGs on de-energized lines and busses creates short circuits, which limit the voltages between the phase and neutral/shield conductors and carry the fault currents to neutral/shield conductors at the work site [1]-[3].

Initially, TPGs consisted of a grounded chain thrown over a line. Later it become a piece of cable with a clamp on each end. The varieties of applications added more complexity to the designs over the years. Today TPG assemblies consist of clamps, ferrules, and jacketed interconnecting cable [3].

There are certain situations with high asymmetrical currents where a single TPG does not have the required rating. In this situation, TPGs may be connected in parallel. This has the advantage of increasing the rating without the need to use heavy and large cross section cables. The application of multiple TPGs reduces the size requirements for any individual TPG assembly.

II. SELECTION OF TPGs

In some situations where a substation is close to a generating station, there are high fault currents present (~80 kA) on utility systems. ASTM F855 specifies the individual TPG ratings for different designs up to 68 kA. In order to safely carry high fault current such as 80 kA, parallel TPGs can be used according to ASTM F855. The standard also recommends that the parallel TPG design configuration be evaluated in the laboratory to verify its suitability for higher fault current.

For this work, a survey was conducted of representatives from approximately 40 utility and manufacturer companies located in North America (represents around 70 million customers) to find the most commonly used sizes and designs of TPGs for high fault currents in the 80 kA range. A 4/0 conductor design was chosen to design a three parallel TPG configuration. Other parts of the TPG design were also chosen from the survey, as specified in TABLE I. All the test samples used for this work were new from the manufacturer. The length of the TPG should be relatively short in order to provide a low impedance path [1]. All the components required to build the TPGs were assembled by the manufacturer and tested at the Nicholas J. Conrad Laboratory in Chicago.

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	6.096 meter (20 feet)
Install torque	Manufacturer specified

III. EXPERIMENTAL DETAILS

A. *Initial Resistance Measurements on TPG samples*

The test samples used for the presented work were new and all the components were assembled according to manufacturer specifications. Each new individual 4/0 TPG was connected to a 5.08 cm (2 inches) diameter bus and the corresponding resistance of the TPG was measured using a DSM600 Micro-Ohmmeter at various current levels and statistical analysis was performed. All TPGs were torqued to the manufacturer specified values. All of the measured resistances met the ASTM F2249 requirements for 4/0 cable size as shown in Figure 1.

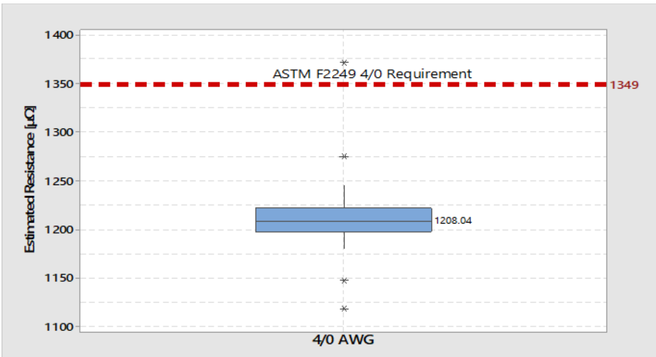


Figure 1: 4/0 TPG Measured Resistances

B. *Laboratory Test Setup, Procedure and Results*

According to ASTM F855-2017, TPGs can be rated for two different types of currents – asymmetric and symmetric [4]. Both faults are 60Hz ac faults; however an asymmetric fault current is a symmetric current with a DC offset. Table I from ASTM F855 defines the rating for symmetrical faults which are classified as having an X/R ratio of $\leq$ 1.8 [4]. Table II from ASTM F855 defines the rating for asymmetrical faults which are classified as having an X/R ratio of = 30 [4]. This X/R ratio equates to a first cycle peak of 2.69 times the RMS current rating.

Most standards recommend de-rating TPGs by at least 10% when an application involves connecting them in parallel [4], [5]. This recommendation is intended to account for unequal current distribution between TPGs. In the presence of high magnitude asymmetric currents, the electromechanical forces are extremely high for which further de-rating of TPGs is required [1]-[5].

In the laboratory testing, three TPGs are connected in parallel between the top input bus and the bottom return bus as shown in Figure 2. The current split was measured by modifying the return bus configuration such that the current through each TPG was forced through a metering shunt before being recombined and returning to the source. The test structures were assembled such that the vertical separation between the input and return buses was 3.048 meter (10 feet) and the horizontal separation between the phase conductors was 1.828 meter (6 feet). The return bus was raised to a height such that when the TPGs were installed, they would not touch the floor.

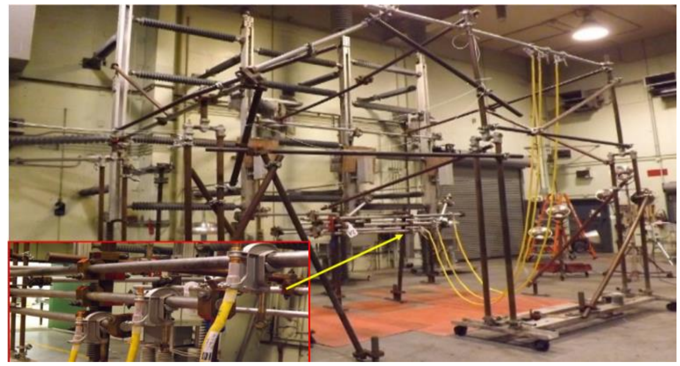


Figure 2: Test setup for three TPGs in parallel with return bus configuration to measure split currents

This test was performed to investigate the current splits in the parallel TPGs for 4/0 cable design and their corresponding fault magnitudes. The sample configuration consisted of three 4/0 TPGs installed side by side 0.305 meter (12 inches) apart. The testing was performed by applying an asymmetric current of 80 kA for 15 cycles (each individual 4/0 TPG is rated for a 47 kA RMS fault current level for 15 cycles according to ASTM F855) with an X/R ratio close to 30. The current split distribution through the individual TPGs was measured. Four replicates of three parallel TPG sets were tested.

During the test, the fault was stopped as soon as an arc was detected. The measured current distribution between each TPG is shown in Figure 3. The variation in the current split between the three TPGs depended on several factors such as resistance, self-inductance and the mutual inductance of a particular TPG with respect to the other TPGs in the parallel configuration. All four replicates failed to withstand the full 15 current cycles. The failures were attributed to the high electromechanical forces between the parallel TPGs.

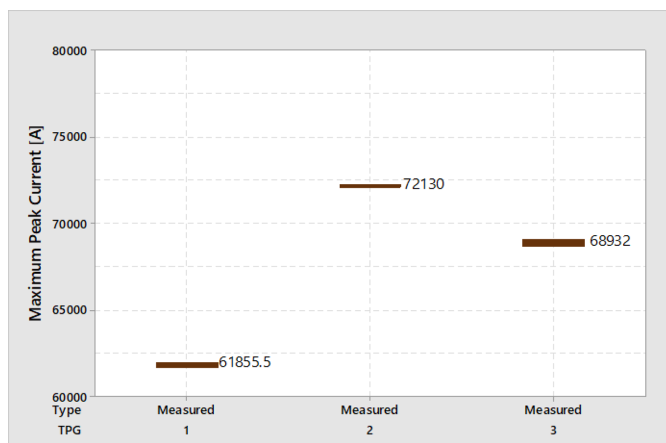


Figure 3: Maximum peak currents per TPG from test data

IV. SIMULATION MODEL DESIGN AND ANALYSES

A. Simulation Model Design

The model was built using MATLAB® Simulink® and is shown in Figure 7. The model consists of a voltage source, an input bus, three TPGs, and measurement components. The input bus consists of a resistor and inductor in series and is used to create the desired X/R ratio. The TPGs consist of a resistance and a mutual inductance module that simulates mutual and self-inductances for the TPGs. An additional inductor and resistor were added to model the bus work to measure the current split used during the test. The incoming fault current along with the individual currents in each TPG are simulated and recorded.

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 1 below [6].

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

Equation 1

Equation 2 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 2 below [6].

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

Equation 2

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 4. 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.

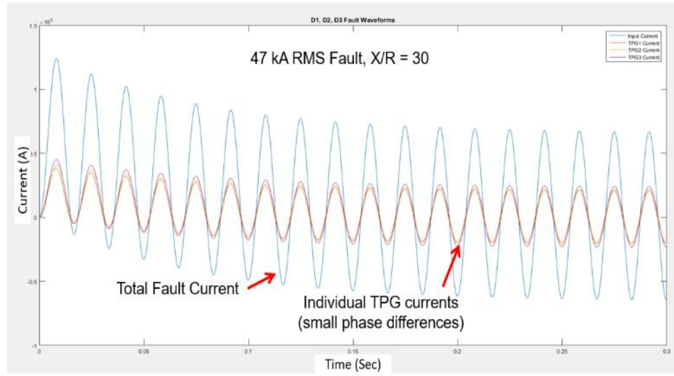


Figure 4: Example Simulation Output Waveform

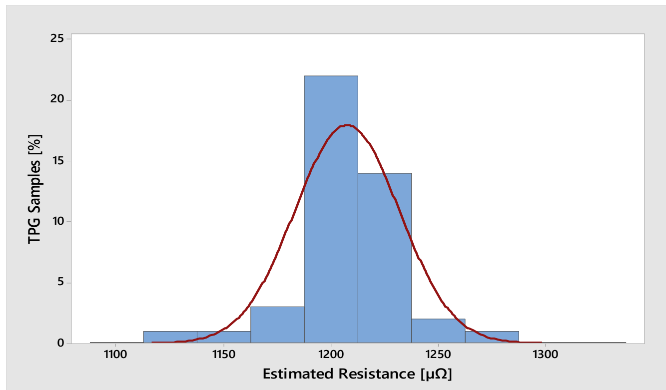


Figure 5: 4/0 TPG resistance distribution used in model

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 shown in Figure 5 which was created using the measured resistances of TPGs used in the testing. The simulation results of the Monte Carlo Simulation when all the three TPGs are connected to a single return bus are shown in Figure 6.

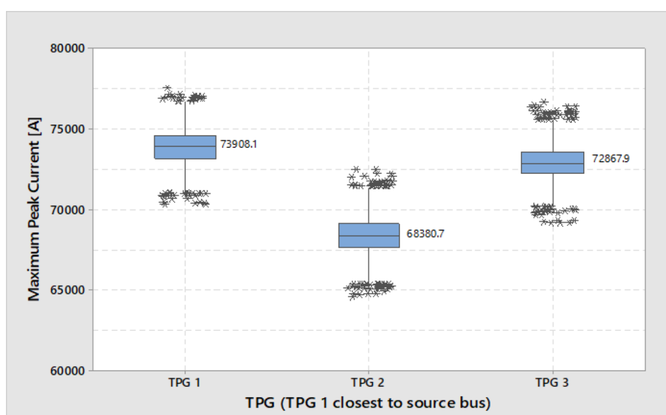


Figure 6: Predicted TPG peak current distributions for 80 kA fault (X/R=30), 0.305 meter (12 inches) spacing between three 4/0 TPGs

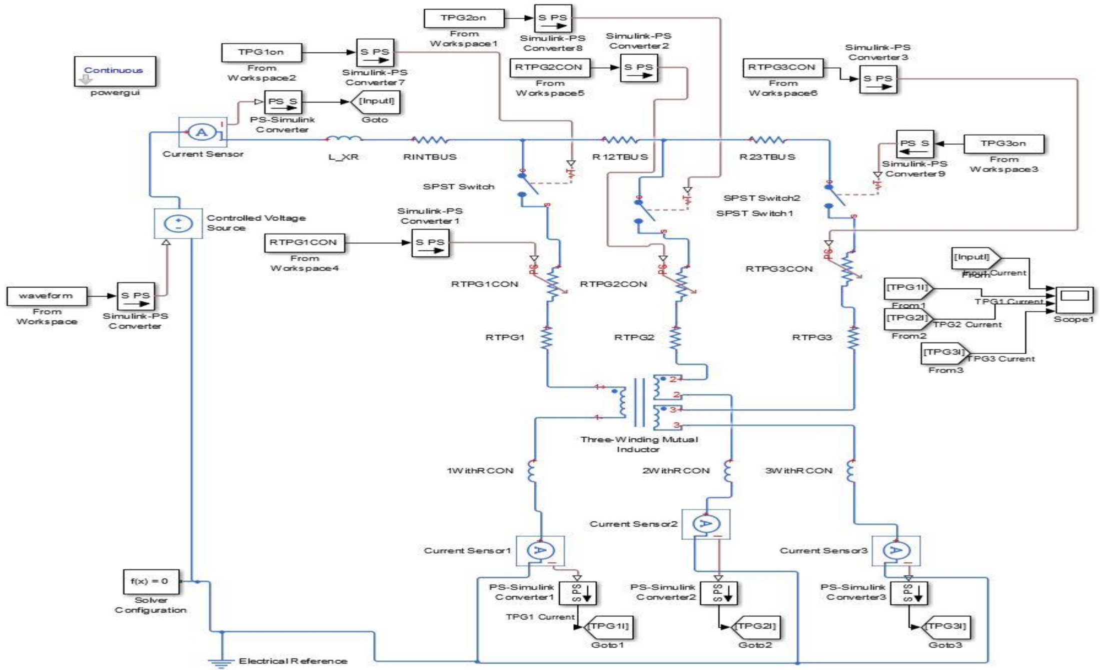


Figure 7: MATLAB Simulink simulation model

B. *Validation of the Simulation Model*

In order to verify the model, actual test data was compared to Monte Carlo simulations and it was noted that the results of the simulation did not match the laboratory results. Further investigation was performed into the differences between the model and the test setup. It was discovered that the additional bus work used to measure the current splits caused unintended additional impedance in the circuit which affected the current split. The additional bus work impedances were estimated and added to the model and the simulation model was run again for 1,000 iterations. With the additional impedances, the simulated peak currents tracked closely to the measured current peaks from the laboratory test results as shown in Figure 8.

Another factor in the verification of the model was to compare the simulated waveforms of the currents to the measured waveforms and ensure that they were similar. Figure 9 shows the first peak of the measured waveform and Figure 10 shows the first peak of the simulated waveforms from the model. The magnitudes and phases of the waveforms closely matched each other. The error percentage between the simulation results and the laboratory test results is approximately 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.

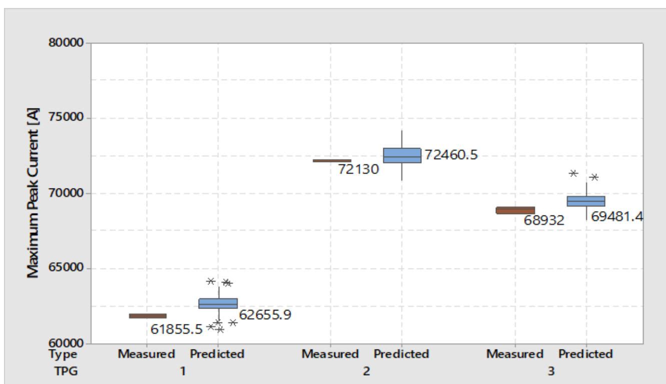


Figure 8: Comparison of simulated peak currents to measured peak currents

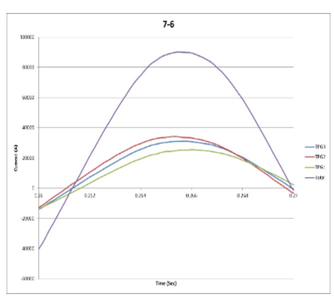


Figure 9: Waveform of Measured First Current Peak in the Laboratory

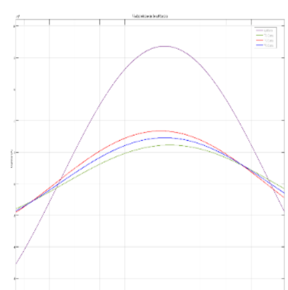


Figure 10: Simulated Waveform of First Current Peak

V. APPLICATION OF SIMULATION MODEL TO OTHER SCENARIOS

The model was used to simulate the current splits in the configuration tested in the high power laboratory. The simulation model was applied to other configurations to see what the effects of changing the parameters of the model were. The main focus was to change the resistances used for the three parallel TPGs.

In the simulations shown previously, all of the TPG resistances were selected from the same resistance distribution shown in Figure 1. 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 on the current splits would be. Using the model, this effect was examined as a proof of concept. The resistances of the TPGs were modified such that the middle TPG of the assembly had the highest resistance as shown in Figure 11.

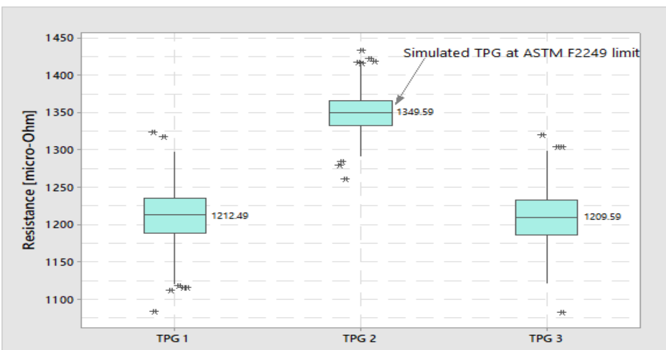
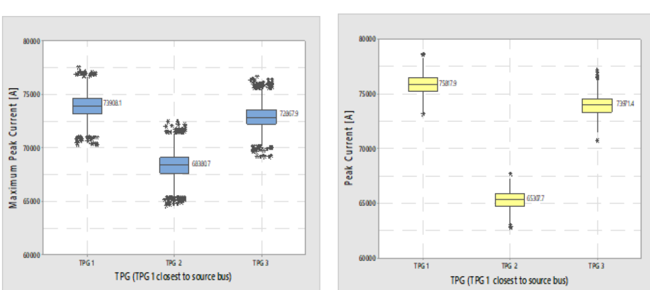


Figure 11: TPG resistances used for model extension

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 12. With the higher resistance cable placed in the middle in a three TPG configuration, the model predicts that the current in the closest TPG to the source will be approximately 2000 A higher.



TPG Resistances used from Figure 8 *TPG Resistances used from Figure 13*

Figure 12: Comparison of peak current splits for model extension with single return bus configuration

VI. CONCLUSIONS

Temporary protective grounds are used to provide safe and reliable protection to personnel while working on de-energized power system equipment which could become energized unexpectedly. During high fault current applications, parallel temporary protective grounds can be used instead of a single TPG with large cross section cable. This paper presents a simulation model to calculate the current split between parallel TPGs in one configuration. Laboratory tests were performed on a three parallel 4/0 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 alter specific system parameters and analyze their effects on the current splits. Users can then 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 the NEETRAC utility and manufacturer members for their sponsorship of this research work. The authors wish to thank the staff at the Nicholas J. Conrad Laboratory, Chicago for their support performing this work.

REFERENCES

Papers Published in Transaction Journals:

[1] James R. White and Shahid Jamil, "Do's and Don'ts of Personal Protective Grounding", IEEE Trans on Industry Applications, Vol.52, No.1, January/February 2016, pp. 677-683.

Papers from Conference Proceedings (Published):

[2] R. E. Mueller and E. F. Richards, "Temporary Protective Grounding of Distribution Circuits – Revisit Ten Years Later", the Proceedings of the Twenty-First Annual North American Power Symposium, 1989, pp. 270-280.

Technical Reports:

[3] U. S. Department of the Interior Bureau of Reclamation Denver, "Personal Protective Grounding for Electric Power Facilities and Power Lines", Vol. 5-1, Colorado, July 2005, pp.1-81.

Standards:

[4] ASTM International Standard Designation F855 – 17, "Standard Specifications for Temporary Protective Grounds to Be Used on De-energized Electric Power Lines and Equipment", 2017.

[5] IEEE 1246, "IEEE Guide for Temporary Protective Grounding Systems Used in Substation", 2011.

Books:

[6] Spartaco Caniggia and Francescaromana Maradei, "Signal Integrity and Radiated Emission of High-Speed Digital System", John Wiley & Sons, Ltd. ISBN: 978-0-470-51166-4, *E-book, 2008, pp.482.*