An Analytical Approach to Examine the Transient Impact of Distributed Energy Resources on Distribution Systems for Protection Studies

Mohammad Nikkhah Mojdehi* and John Viglione†
*Energy and Microgrid Group, O'Brien and Gere Engineers, 333 W Washington St, Syracuse, NY 13202
Email: mohammad.mojdehi@obg.com
†National Grid, 300 Erie Blvd West, Syracuse, NY 13202
Email:John.Viglione@nationalgrid.com

***Abstract*—The next generation of electrical distribution systems (EDSs), with increasing penetration of distributed generation resources (DERs), represent complex energy systems with multiple functionalities. One of those functionalities is to improve the resiliency through formation of a microgrid. An ideal microgrid is capable of seamless transition from grid-tied to island state of operation. However, microgrid protection is one of the challenges faced by utilities. Since each EDS may have unique characteristics, overcoming this challenge requires an accurate modeling and simulation tool. In this paper an analytical tool is presented to assist utilities protection engineers in investigating the effectiveness of microgrid protection schemes. The tool uses raw data from utilities' existing database and generate accurate model of the EDS. The model can be used as a plug-and-play platform for different types of protection analysis. Simulation results of a real case study show the accuracy and functionality of the tool.**

I. Introduction

Evolution of electrical infrastructure initiated by adoption of new technologies and policies has led to opportunities as well as challenges. In order to have a clear understanding of challenges, it is useful to categorize the electrical infrastructure into three major groups: Generation, Transmission, and Distribution. While generation and transmission have been the center of power industries research and development, the distribution section has been remained largely unchanged over the past several decades. In many locals, 4.8 kV radial delta systems which were erected in the 30's and 40's, are still in service. However, new electrical distribution systems (EDSs) are built primarily as wye grounded radial systems.

Mandatory policies supporting the adoption of distributed energy resources (DERs) and energy resiliency, emphasize the need to re-think the design of EDSs. Therefore, a new vision for EDS planning and operation is necessary to address all existing weaknesses and propose new solutions. New York state is leading the effort to create the vision through its reforming the energy vision (REV) initiative. REV is aimed to encourage utilities to integrate sustainable generation sources into the design of EDS. However, due to the lack of a comprehensive analytical tool, modeling and managing the impact of any change/upgrade on EDS is complicated.

The next generation EDSs must be capable of interconnecting DERs, utilizing intelligent electronic devices, improving resiliency of power delivery, and capturing market and end-user dynamics. Therefore, the next generation EDSs represent multi-domain complex systems and there is no comprehensive analytical tool to respond to all concerns and challenges simultaneously [1].

Microgrid capability is an approach to improve the EDS resiliency. A system with microgrid capability is operable in both modes, grid-connected and island. If the main grid is not present, the microgrid capability allows EDS to be operated in island mode and serves end-users. For safe and reliable operation of the microgrid, protection of the microgrid in both grid-connected and the island modes against all types of faults is essential [2]. Since the very basics of conventional network operation (such as radial topology and passive nature of distribution feeders) do not hold true any more, revolutionary changes are required for safe operation [3]. The level of penetration of DER and the type of interfacing scheme, that is whether the DER system is based on direct coupling of rotating machines or a power electronic converter, have a fundamental impact on the protection scheme of the microgrid [4]. Therefore, each EDS may have characteristics that are unique unto itself only. An analytical tool for accurate modeling and simulations is required to determine an applicable and effective protection scheme for the EDS.

Most commonly-used software applications in the utility industry are steady-state software applications. Considering the complexity of the next generation EDSs and diversity in DERs technologies, steady-state software applications may not be sufficient for EDS modeling and simulations. However, those software applications can provide already structured database of load information, layout of the EDS, and the different electrical parameters of the network equipments. Therefore, designing a new simulation environment which can exchange data with existing software applications and perform time-based analysis would be a cost-effective approach to overcome the gap. In this way, the cost imposed by personnel training and adapting the existing database would be avoided.

In this paper, an analytical tool is presented to investigate the effectiveness of protection schemes for the microgrid. Although several microgrids protection scheme have been reported in the literature [5]-[8], due to the unique characteristics of each EDS, their applicabilities might be limited. A typical DER interconnection in a real case study was examined by the developed tool and the simulation results conform the expected results. Therefore, the developed tool would help utilities engineers to investigate the protection challenges of the microgrid and validate potential protection solutions. The tool uses a plug-and-play platform which can include each component of the microgrid. In another words, a unit (load, generation, transformer and etc.) can be placed at any point on the EDS model without re-engineering the platform.

II. Microgrid Protection

Utilities primarily use delta-wye transformers in EDSs to connect the transmission system to the EDS (delta on the high voltage side and wye on the low voltage side). EDSs are usually three-phase, four-wire, multi-grounded systems. The transformer at the substation has a solidly grounded neutral. Almost at every point of common coupling (PCC) of each DER an interconnection transformer is used to match the voltage between the DER and the EDS. The transformer connection can be wye, grounded wye, or delta on primary or secondary side. Usually the secondary side of the interconnection transformers (on high voltage side) is delta or ungrounded wye. Fig. 1 illustrates the typical EDS with interconnected DER.

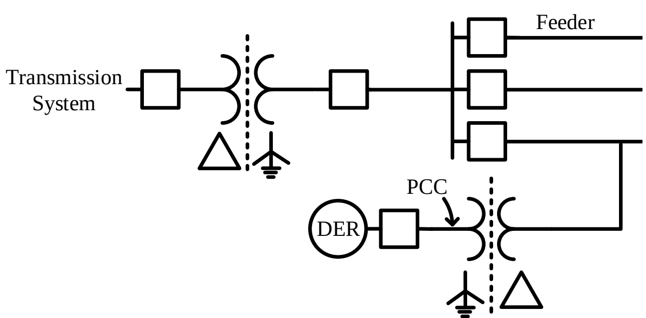

Fig. 1. Typical EDS with interconnected DER.

On a radial feeder with a solidly wye grounded substation, all equipments operate within the phase-to-ground voltages established during normal conditions. Faults on the feeder decrease the phase-to-ground and phase-to-phase voltage. Interconnected DERs cause complications to design of EDSs protection. The key protection issues of EDS with interconnected DERs are fault current level modification, reduction in reach of relays, bi-directionality and voltage profile change, sympathetic tripping, islanding and effect on feeder reclosure [4]. In order to illustrate the impact of DERs on EDS protection, a scenario is considered.

When a fault occurs on the feeder and the feeder breaker trips to clear the fault, it also removes the ground source for the feeder. If the DER remains energized in an island mode, the ground fault may still be present and will not be detected using traditional protection schemes [9]. As shown in Fig. 2, a Phase A-to-ground fault collapses the faulted phase to zero Volt while the unaffected phases will remain at nominal phase-to-neutral values. Once the feeder breaker operates the faulted phase will now be referenced to the ground while the un-faulted phases will jump as high as 173%.

For ungrounded isolated microgrids, two major ground fault current magnitude-limiting factors are the zero sequence

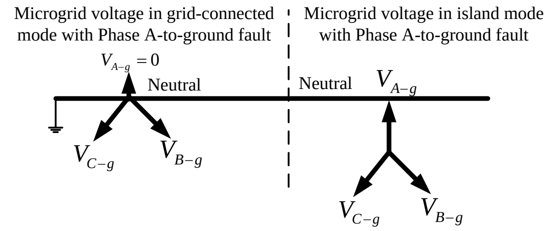

Fig. 2. Voltage level of a microgrid during a phase-to-ground fault.

line-to-ground capacitance and fault resistance. Self-extinction of ground faults in overhead-ungrounded lines is possible for low values of ground fault current. At higher magnitudes of fault current, faults are less likely to self-extinguish at the fault current natural zero-crossing because of the high transient recovery voltage [10]. Zero-sequence, or three-phase voltage relays can detect ground faults in ungrounded systems. This method of fault detection is not selective and requires sequential disconnection or isolation of the feeders to determine the faulted feeder.

For ground faults that remain after the utility source has been removed from the feeder, 3V0 detection schemes are used for detecting the ground fault. A 3V0 scheme requires a high side grounded wye/open corner delta low side and a voltage sensing relay. When voltage is normal on the feeder, the 3V0 voltage is very low [11]. If a fault occurs as described above, 3V0 increases, which detects the condition so the DER can be disconnected. Since the major purpose of operating a microgrid in an island mode is the resiliency, tripping DERs during a fault may not serve the goal. Therefore, developing an innovative solution which yields to a safe and reliable operation of islanded microgrid during any fault type is necessary. However, an analytical tool for modeling and simulation of the microgrid and its components is missing. Since the protection considerations for DERs may vary depending on the particular EDS to which they are connected, the tool must be DER and EDS agnostic. Next we present an analytical tool which can be used for analyzing microgrid protection schemes.

III. Microgrid Analytical Tool

Utilities' commonly-used software applications are mainly steady-state analytical tools, such as CYME/CYMDIST. These tools provide accurate results when the feeder is connected to a system with adequate inertia to support the time margins required for stable results. Those tools may not be adequate for analyzing the same feeder when interconnected as a part of a microgrid. However, steady-state software applications can provide already structured database of EDSs. It would be desirable to link existing electric power simulation tools with an innovative analytical tool to perform required analysis. In this section, the developed time-based analytical tool for the microgrid analysis is described.

DERs are connected to distribution feeders, therefore generating an accurate model of the feeder is the first step in the development of the tool. However, the size of the feeders and number of elements in the feeders make this step complex and time consuming. The developed tool utilizes the raw EDS data from other software applications to create the accurate

EDS model in an automated fashion. The raw data includes nodes, lines (three-phase or single phase line which could be underground or overhead cables), transformers, capacitor banks, regulators, and loads. Creating the feeder topology and detecting the nodes and other components connectivities is the key part in the distribution feeder modeling.

A simple methodology has been used in the developed tool to detect distribution feeder topology, nodes conductivities, and all paths from substation to the end nodes of the feeder. The methodology which can be applied on normally open loop EDSs with any size and number of nodes, works based on the graph theory. A normally open loop EDS can be considered as a tree graph G which is connected and has no loop. Therefore the distribution feeder can be modeled as a connected directed tree graph with n vertices and $n-1$ edges. A color can then be assigned to each node, using the coloring approach by Welsh and Powell [12]. Using the assigned colors, the tool creates the topology of the feeder by levlizing the nodes.

Before levelizing the nodes, three types of nodes are defined based on the degree of a node: End node; Junction node; and Interconnected node. End node is a node in the graph with degree of one. If the distribution system has a single feeder, then the source node will have a degree of one but it should be noticed that it is not an end node. Junction node is a node with the degree of 3 or more. These nodes send power to more than one downstream nodes. Since EDS is modeled as a directed tree, it should be mentioned that there is just only one way from each node to its upstream node. Interconnected node is a node with the degree of 2.

Fig. 3 presents the flowchart used for levelizing the nodes. The developed tool starts with the substation node or source node. This node is referred as the first level of the graph. The degree of the source nodes is equal to the number of feeders (branches) leaving the node. The tool will then go through all branches leaving the source node, till faces the end node. Whenever a junction node is reached, it increases the level. So each junction node will increase its level. The number of level is considered as the color of each junction node. Level 1 is assigned to the source node as its color. There are three states for position of interconnected nodes. They could be between level 1 (source node) and a junction node level, between two junction nodes levels, or after the last junction node level (between junction node and end node). If they are between the level 1 and a junction node level, color 1 will be assigned to them. If they are between two junction nodes levels, the color of the upper junction node level will be assigned to them. If they are after the last junction node, the color of the last junction node level will be assigned to them. After this step, the tree graph representing the feeder is levelized.

After levelizing the graph and assigning a color to each node, the tool detects the connectivity of nodes and find the path from each end node to the source node, as shown in Fig. 4. The number of paths in the graph is equal to the number of end nodes of the graph. The key point here is when the tool reaches a junction node. If the tool reaches an interconnected node then there is just one way to continue, however when it reaches a junction node, there are more than one way to continue. Just one branch from junction node leads to the upper level (color with lower number) node. So in this situation, the tool checks the color of all adjacent nodes which have been assigned in the previous step. The tool will continue by the adjacent node which has a color with lower number.

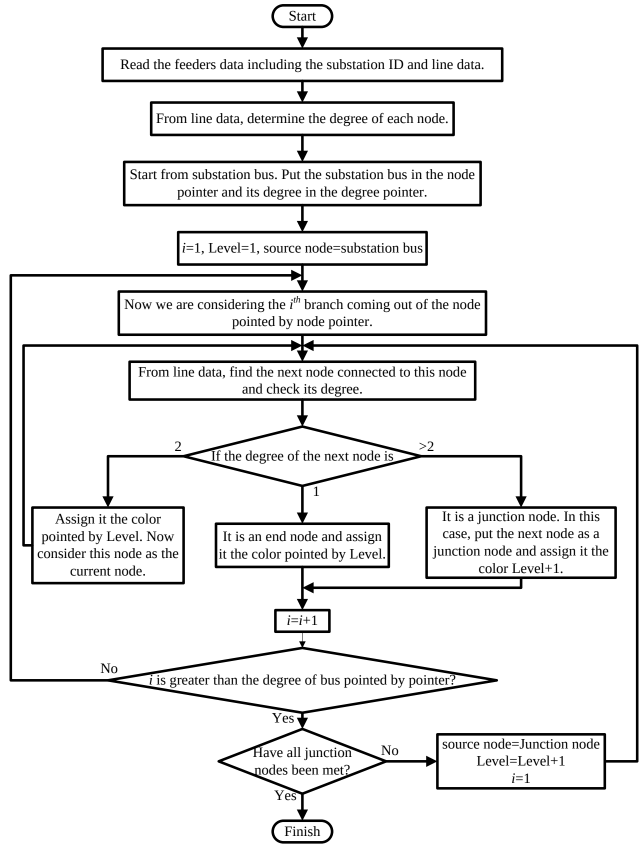

Fig. 3. Flowchart of assigning color to each node.

At this step, the tool configured the feeder topology. The result then is used to generate the accurate model of the feeder. Due to the MATLAB/SIMULINK and its SimPowerSystems library capabilities in modeling and simulations, MATLAB/SIMULINK has been used as the software platform in this paper. Three-phase VI Measurement block has been used to model each node. Also a Three-phase Mutual Induction block has been used to model each feeders section. The input parameters for a Three-phase Mutual Induction block are the zero and positive sequence impendence of the line. These information can be easily obtained from the raw data. The feeder model can simulate different operating condition in a plug-and-play fashion. DERs can be plugged into the model by connecting their module to PCC node in the EDS.

Among all DER technologies, photovoltaic (PV) systems have attracted considerable attention and investment in several countries, such that a significant penetration of PV systems into the EDSs is anticipated. Therefore, the focus of this paper is on PV systems. For faster simulations, considering the complexity of EDS, an equivalent dynamic average-value model of PV system has been used. In such a model, which is known as averaged model, instead of applying switching scheme, terminal variables of the PV converter are approximated by their respective per-switching-cycle moving average values [13].

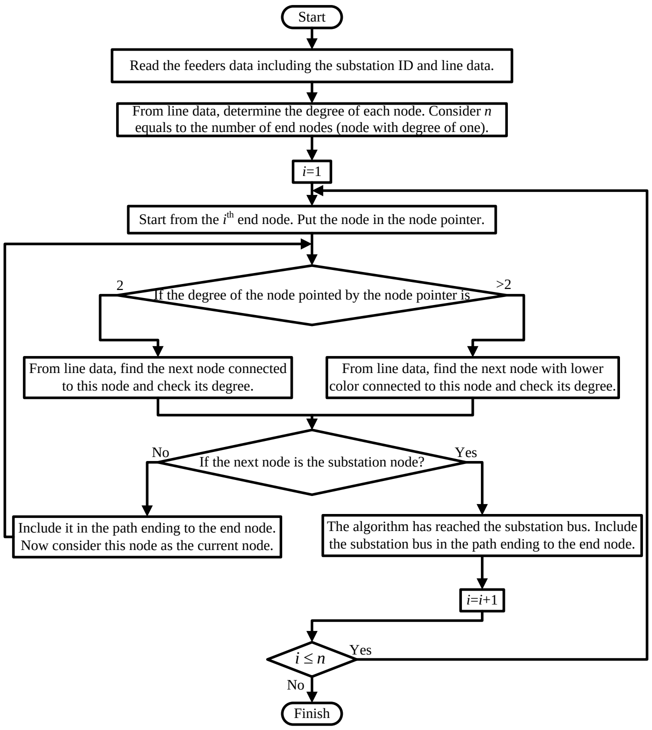

Fig. 4. Flowchart of tracking all paths from each end node to the source node.

IV. Results and Discussion

The developed co-simulation platform was tested on an actual case study. The case study represents a distribution feeder in National Grid USA operating region in Northeastern U.S. The feeder is four-wire multi-grounded neutral overhead distribution feeder operated at 13.2 kV, as shown in Fig. 5. feeder contains 1614 nodes, 1613 branches, 5 fixed shunt capacitor banks, and 10 transformers. Two PV plants, PV plant 1 and PV plant 2, are connected to the feeder. The feeders measured peak and minimum daytime load during the past twelve months were approximately 6.584 MVA and 2.97 MVA, respectively. PV plant 1 is composed of 4 inverter modules, each with 500 kW capacity. The total capacity of PV plant 1 is 2 MW. PV plant 2 is composed of 6 inverter modules, each with 500 kW capacity. The total capacity of PV plant 2 is 3 MW. Both PV plants are connected to the feeder with a step up 0.48 kV (delta)/13.2 kV (wye grounded) transformer with the PCC at the 0.48 kV connection to the utility.

The raw feeder data used for simulations was acquired from the existing feeder's CYME file. The data was then processed and the accurate model of the feeder with all components was generated by the developed tool. In order to simulate the microgrid behavior during an islanded-mode operation, the main grid was disconnected at the main substation. The PV plants output and loading condition of the EDS have been adjusted to operate the EDS as an island.

A temporary Phase A-to-ground fault has been applied on the distribution feeder at 0.05 Second and has been cleared at 0.2 Second. Fig. 6 shows the current and voltage at the fault location. As can be seen from the figure, after transitioning to the island-mode operation, the current and voltage values are at nominal values. After the occurrence of the fault, voltage of Phase A is zero however the other phases voltage are increased. Also the Phase A current are increased due to the faulted phase. That implies that all sequence values are increased due to the Phase A-to-ground fault.

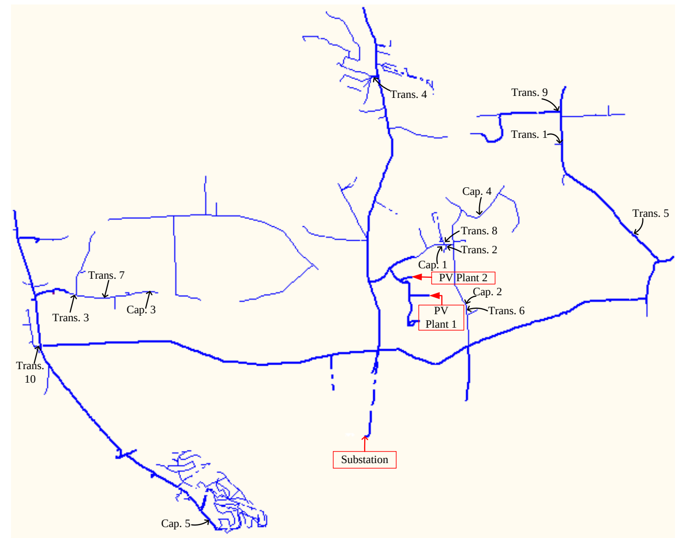

Fig. 5. Single line diagram of the distribution feeder.

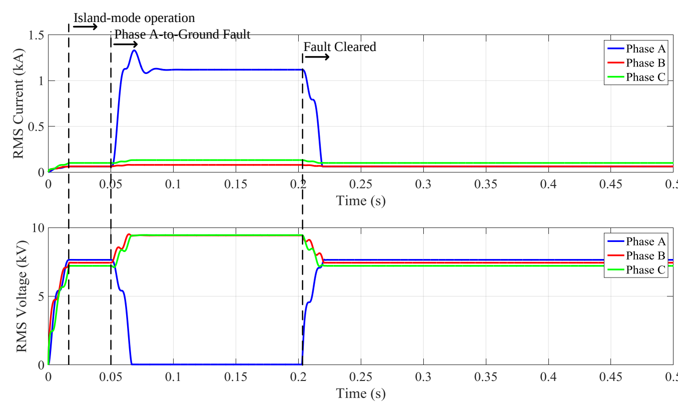

Fig. 6. Current and voltage at fault location.

Due to the transformer configuration, loss of the utility ground, zero sequence values (current and voltage) at PCC of PV plants are negligible. Fig. 7 to Fig. 9 show the positive, negative, and zero sequence of current and voltage at PCC of PV plant 1 and PV plant 2. Also, from the figures, one can see that the symmetrical components of voltage and current at PCC remain unchanged after the fault.

The generated graphs from the time-series analysis conform to the expected results. With a ground remaining on the EDS, neutral displacement is limited, faulted phase voltage behaves consistent with traditional protection schemes for defined system characteristics. This concludes that the time-based developed tool is effective. The developed tool will allow protection engineers to explore non-traditional sources interfaced with traditional EDSs to define/predict issues and solutions.

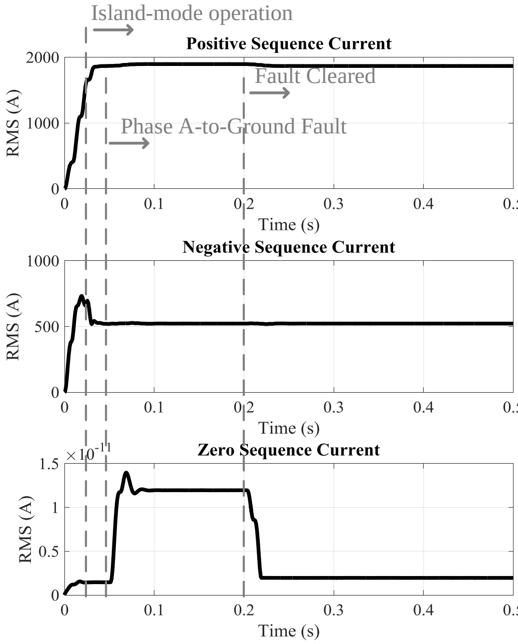

Fig. 7. Positive, negative, and zero sequences of current at PCC of PV plant 1.

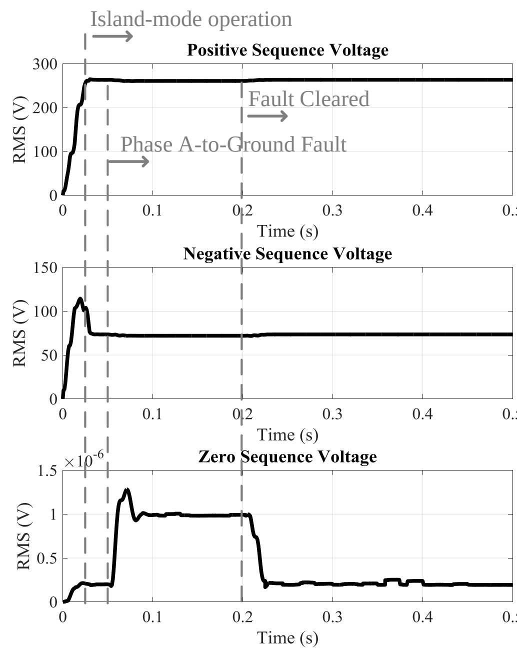

Fig. 8. Positive, negative, and zero sequences of voltage at PCC of PV plant 1.

V. Conclusion

An analytical tool was presented in this paper which can be used to investigate the effectiveness of microgrid protection schemes. The developed tool generates an accurate model of the EDS using utilities existing databases, in an automated fashion. The model is then used as a plug-and-play platform to incorporate different components such as DERs. Therefore, microgrid protection challenges can be analyzed by utilities

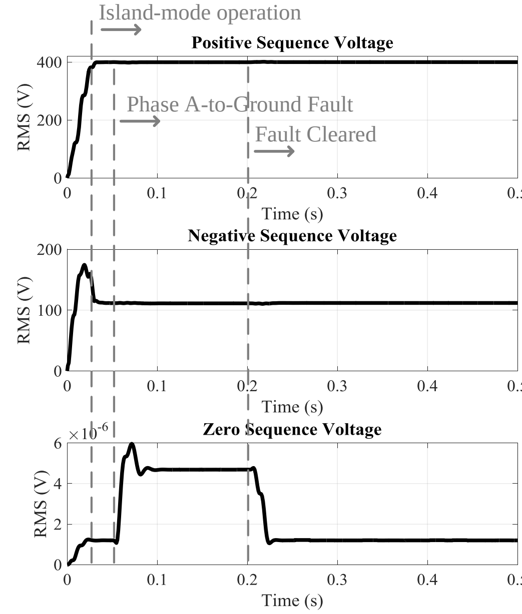

Fig. 9. Positive, negative, and zero sequences of voltage at PCC of PV plant 2.

engineers in a reliable and cost-effective manner. The tool was successfully used in a real case study. Results clearly indicate the simplicity, efficiency, and accuracy of the tool.

Acknowledgment

The authors would like to thank National Grid USA for their support.

References

[1] M. A. Moffet and D. Beauvais, ”Review of open source code power grid simulation tools for long-term parametric simulations”, Natural Resources Canada, Tech. Report 2011-137, 2011.

[2] H. Nikkhajoei and R. H. Lasseter, ”Microgrid protection,” *IEEE Power and Energy Society General Meeting*, pp. 24-28, 2007.

[3] T. S. Ustun, C. Ozansoy, and A. Zayegh, ”Fault current coefficient and time delay assignment for microgrid protection system with central protection unit,” *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 598-606, 2013.

[4] S. M. Sharkh, M. A. Abusara, G. I. Orfanoudakis, and B. Hussain, ”Power electronic converter for microgrids,” John Wiley & Sons, Inc, 2014.

[5] K. O. Oureilidis and C. S. Demoulias, ”A fault clearing method in converter-dominated microgrids with conventional protection means,” *IEEE Transactions on Power Electronics*, vol. 31, no. 6, pp. 4628-4640, 2016.

[6] C. Wang, X. Yang, Z. Wu, Y. Che, L. Guo, S. Zhang, and Y. Liu, ”A highly integrated and reconfigurable microgrid testbed with hybrid distributed energy sources,” *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 451-459, 2016.

[7] M. A. Haj-ahmed and M. S. Illindala, ”Investigation of protection schemes for flexible distribution of energy and storage resources in an industrial microgrid,” *IEEE Transactions on Industry Applications*, vol. 51, no. 3, pp. 2071-2080, 2015.

[8] T. S. Ustun and R. H. Khan, ”Multiterminal hybrid protection of microgrid over wireless communications network,” *IEEE Transactions on Smart Grid*, vol. 6, no. 5, pp. 2493-2500, 2015.

[9] J. Simms and G. Johnson, ”Protection considerations for installation of distributed energy resources,” *68^th Annual Conference for Protective Relay Engineers*, 2015.

[10] J. Roberts, H. J. Altuve, and D. Hou, "Review of ground fault protection methods for grounded, ungrounded, and compensated distribution systems," Schweitzer Engineering Laboratories, Technical Paper.

[11] D. D. Ronde, R. VanHatten, and A. Wade, "Loss of effective system grounding - best practices, protection challenges, and solutions," *Annual Georgia Tech Protective Relaying Conference*, pp. 1-8, 2014.

[12] D. J. A. Welsh and M. B. Powell, "An upper bound for the chromatic number of a graph and its application to timetabling problems," *The Computer Journal*, vol. 10, no. 1, pp. 8586, 1967.

[13] A. Yazdani, A. Rita Di Fazio, H. Ghoddami, M. Russo M. Kazerani, J. Jatskevich, K. Strunz, S. Leva, and J. Martinez, "Modeling guidelines and a benchmark for power system simulation studies of three-phase single stage photovoltaic systems," *IEEE Transactions on Power Delivery*, vol. 26, no. 2, pp. 12471264, 2011.