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Characteristics of symmetrical components for high impedance faults in distribution networks with photovoltaic inverters

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ABSTRACT

This work models a photovoltaic (PV) inverter connected to an IEC microgrid system. The purpose of this study was to find the characteristics of symmetrical components before and after a high impedance single phase short-circuit fault. The IEC microgrid system is tailored to the distribution system in Indonesia, where the applied voltage is 20 kV. Only parameters related to the short-circuit study are included in the model. A second-order generalized integrator frequency-locked-loop is utilized to represent the 3-phase PV inverter. The inverter model, previously treated as an ideal current source, and positive sequence current are no longer employed, as they fail to depict the characteristics of symmetric components during a phase-to-ground short-circuit fault. The IEC microgrid system connected to the PV inverter is simulated using ATPDraw-electro magnetic transient program (EMTP). Simulation results reveal that the changes in the symmetric component values of current after a fault experience a very insignificant increase. Meanwhile, the positive sequence voltage values following the short-circuit fault exhibit a negligible decrease. In contrast, the negative sequence and zero sequence voltage components after the short-circuit fault undergo a significant increase.

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1. INTRODUCTION

In recent years, shifting global trends in the use of new and renewable energy sources have caused the integration of photovoltaic (PV) into distribution networks to experience rapid growth. In application, PV is equipped with an inverter so that it can be connected to a 3-phase alternating current (AC) distribution network. This combination of PV with an inverter will create several challenges in operating the electric power distribution system, because the transformer used is not like the one used in the substation [1]. Among them are related to distribution network management short-circuit perturbation represents the preeminent perturbation phenomenon that manifests in distribution networks [2], [3], and poses a grave peril to the sustenance of uninterrupted provision of electrical power. The old methods used for short-circuit fault analysis and protection system design can only work well for distribution networks that are not connected to new and renewable energy sources. One type of fault that often occurs in the distribution network is phase-to-ground short-circuit faults with high impedance fault. Most of these disturbances are caused by plants touching conductors in the distribution network [4]. The characteristic of a high impedance fault is a low fault current value [5]. The fault current is estimated to be only 10% of the normal load current [6].

Distribution networks that are connected with PV inverters exhibit dissimilarities in terms of short-circuit currents when juxtaposed with networks that are solely linked to loads and provide power with steady and unvarying magnitudes. The present perturbations in PV inverters exhibit a significantly reduced magnitude in comparison to synchronous generators, which can be attributed to the constrained generation of reactive power by PV inverters [7]–[9]. The values of zero sequence and negative sequence current disturbances are difficult to detect because the disturbances are very small [10]. The contribution of PV inverter current disturbances is limited to around 120% of the nominal current by the inverter controller [11]–[13] and is not influenced by the system source impedance [14]. Inverter control strategies are incapable of constraining current disruptions in the presence of asymmetrical disturbances due to the absence of negative sequence current elements [15], [16]. The performance of PV inverters is adversely affected by transient events, as PV inverters are categorized as a variant of current source converters [17], [18]. The condition at hand will have an impact on the performance of the existing protection system. The existing system for protecting the distribution network can only be utilized in networks where there is a direct flow of current [19]. The magnitude and direction of current disturbances will change due to the presence of PV in the distribution network [20]. The magnitude of the disturbance caused by the current will be determined by the size and quantity of the PV systems installed in the system [21].

The most commonly employed method for observing the response of the inverter to short-circuit disturbances is to model it as an ideal current source and represent its positive sequence current [6], [22]. The star-delta transformer connected to the inverter model can only be used as a source of positive sequence current the inclusion of this transformer will prevent the occurrence of zero sequence voltage when there is a single-phase fault to ground, thereby causing a disturbance in the symmetry of the fault current [23]. It is not feasible to model the inverter solely as an ideal current source consisting of DC current based on the provided description, as it will not provide accurate feedback in the event of a single-phase fault to ground an analysis of the impact of PV fault current on the subtransient phase during a short-circuit fault is conducted by [24]. Analyses of symmetrical and asymmetrical short-circuit faults are carried out using an inverter model with current control diagrams described in [3] and and voltage control diagrams described in [25] are conducted. The nodal admittance matrix factorization approach is employed to perform the short-circuit analysis [26]. Previous studies have used symmetrical components to analyze the behavior of PV systems. The study conducted in [27] analyzed the effect of transformer configuration on PV systems during unbalanced disturbances using symmetrical components. Harzig *et al.* [28] analyzed unbalanced disturbances using modified symmetrical components for current-controlled inverters. By taking into account the inverter control, output filter characteristics, and unbalanced load as the basic for developing a symmetrical component model.

Until now, no analytical model can be used as a suitable tool to expose the characteristics of faults in distribution networks connected to PV inverters, such as synchronous generators [29], [30]. Research has been done to analyze disturbances on PV inverters using the following methods: electromagnetic transients [31], [32], constant current [33], [34], and constant power models [33], [35]. Electromagnetic transient modelling is costly to calculate, so it is not suitable for large system studies [36] and requires restricted data from inverter manufacturers on the other hand, the other two methods are not reliable in presenting the characteristics of the fault current due to the time-dependency of the inverter fault current contribution [37]. Extensive studies have been conducted on the response of inverters to disturbances using time domain simulations [38] with the use of an electromagnetic transient inverter model, as well as experimental studies [39], [40]. However, many researchers have identified the need for analytical fault models of inverters [33] in order to facilitate accurate and efficient protection studies on a large scale. However, the response of the fault current in the inverter at the fundamental frequency during grid disturbances cannot be fully elucidated by the currently available models in the existing literature. The reseacher in the [41], [42] have presented a fault model of the inverter through an analytical approach, considering a current limiting method to restrict the inductor current. In the case of a PQ source inverter, the model solely focuses on the controller's impact on the inverter's fault response, disregarding the influence of inverter hardware components and the requirements of standard/grid codes. The fault characteristics of PV inverters with two distinct control modes, namely current control and voltage control, have been examined in [43]. Based on the control of sequence current and the provision of reactive power during network disturbances, [33] has proposed a method for calculating short-circuit current in multi-PV inverter systems. The authors assume that the inverter functions as a constant power source, where the desired power relies on the provision of reactive power during grid disturbances. However, in reality, the inverter can operate in other modes as well. Furthermore, the method presented in the study does not offer a means to determine the magnitude of different fault currents observed in the initial cycles following the occurrence of a fault. [37] suggests modeling the short-circuit current contribution of a type IV wind farm as a finite current source, with values ranging from 2 to 3 per unit for the first one to two cycles, and 1.5 per unit thereafter while this model is relatively simple, it may not accurately represent the actual fault response observed in experiments by employing the concept of a controller-based equivalent circuit, a phasor-domain short-circuit model has been proposed for a type IV wind turbine generator in [44] and for a type III wind turbine generator in the [45]. These models can be applied to other PV inverters, considering various control schemes, transient functionality, split-sequence control, and disturbance ride-through capability. The models offer steady-state fault currents through iterative solutions. Certain commercial software also utilizes similar models for type III and type IV wind turbine generators [46]. Nevertheless, these models do not offer insights into how the current in PV inverters transitions from the pre-fault current to the steady-state fault current, and do not explain the initial surge in current observed during faults, which is commonly observed in PV inverters.

The objective of this research paper is to analyze the characteristics of a grid-connected single-phase high impedance fault (HIF) PV inverter. An IEC microgrid model connected to a PV inverter has been developed using ATPDraw-electro magnetic transient program (EMTP). Subsequently, short-circuit disturbances are simulated on this model. The employed inverter model is an embodiment of a three-phase second-order generalized integrator (SOGI) frequency-locked-loop (FLL) with gain normalization [47]. The essence of this study lies in its capacity to furnish insights into the manifestation of symmetric current and voltage components in the event of a single-phase fault to ground. Where these characteristics are an important part of developing protection schemes for distribution networks that are integrated with PV inverters.

2. METHOD

The initial step of this research is to model the IEC microgrid system, as shown in Figure 1. The characteristics of symmetric current and voltage components from each PV inverter during a short-circuit fault will be observed. The changes in the values of symmetric components before and after the fault will be the focus of the observation. Simulations are conducted for 500 ms with a sampling rate of 10 kHz. The system frequency applied follows the IEC standard, which is 50 Hz.

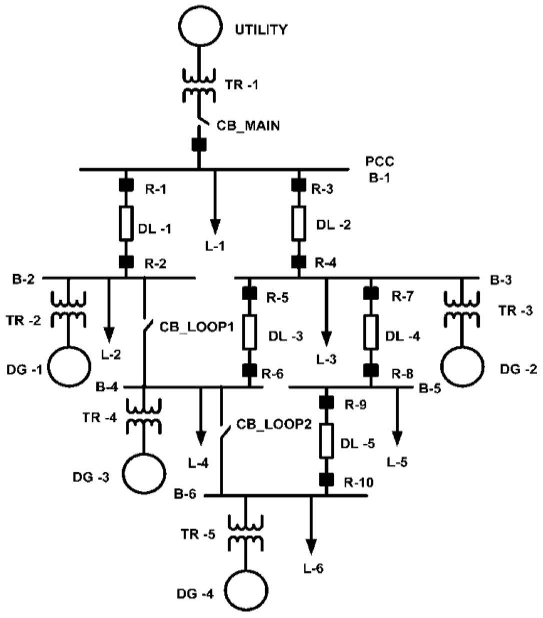

Figure 1. Microgrid IEC system

2.1. Distribution system modeling

The modeling of the IEC microgrid system is done using ATPDraw-EMTP. The model is connected to three PV distributed generation. An inverter, serving as the interface between PV and the distribution network, is added to this IEC microgrid system. This inverter will generate a three-phase output and is connected to buses B-2, B-4, and B-6. The location of the short-circuit fault is set at bus B-5. Measurement components for current, voltage, and symmetric components are installed in this ATPDraw-EMTP model to obtain the required parameter values. Figure 2 depicts the complete model of the IEC microgrid system using ATPDraw-EMTP.

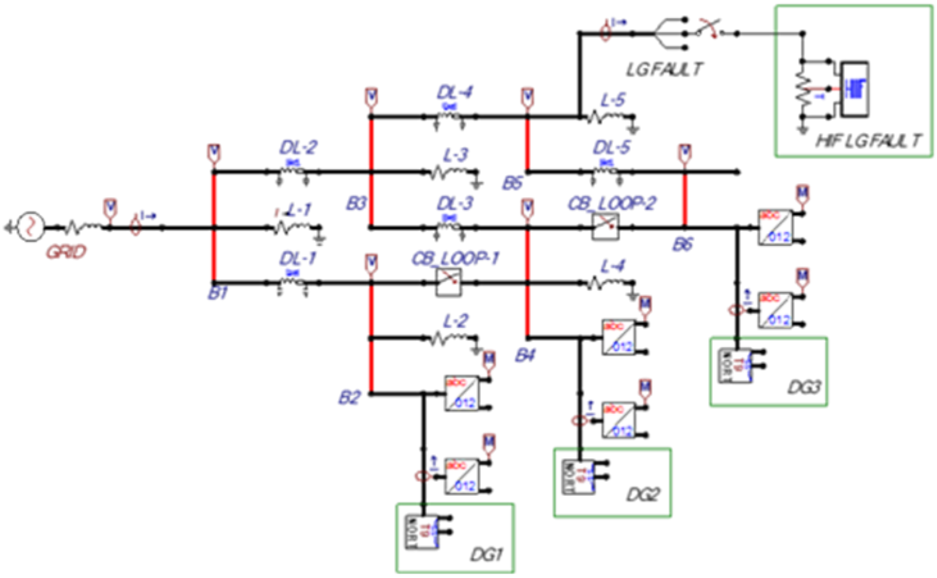

Figure 2. IEC microgrid ATPDraw-EMTP model

2.2. PV inverter modeling

The PV inverter model connected to the IEC microgrid system has a capacity of 600 kW, connected to bus B-2. Meanwhile, PV inverters connected to buses B-6 and B-4 have a capacity of 100 kW each. These PV inverters are modeled to be directly connected to the 20 kV distribution network without the use of transformers. The PV inverters are operated to supply maximum power to the system according to their capacity.

2.3. High impedance fault modeling

The HIF equation is modeled using ATPDraw-EMTP. Figure 3 shows the application of the transient analysis control system (TACS) model, to obtain time-varying fault resistance values. The model is an application of the differential equations applied by [48]. This fault resistance is placed on phase B, as seen in Figure 3.

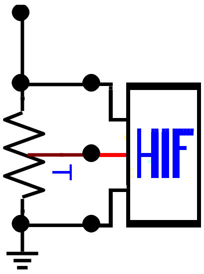

Figure 3. ATPDraw-EMTP high impedance single phase fault model

3. RESULTS AND DISCUSSION

3.1. Symmetrical component of the current

The complete tabulation conclusion of the simulation current value for a single-phase fault is shown in Table 1. The simulation results show that the positive sequence current value before the fault occurs for inverter 1 is 22.705 A, PV inverter 2 and PV inverter 3 is 2.4455 A. After the sequence current fault occurs, positive PV inverter 1 increased to 23.153 A, and 2.5438 A. Meanwhile, all PV inverters showed a negative sequence current value of 0 for negative sequence current. After a disturbance, the negative sequence current of PV inverter 1 was -0.0572 A and -0.058 A for PV inverter 2 and 3. Zero sequence current before fault occurs is 0 A for all PV inverters. After a disturbance, the zero sequence current from PV inverter 1 is 0.0106

A and 0.0107 A for the zero sequence current of PV inverter 2 and 3. The simulation results showing the zero, positive and negative sequence current values are shown in Figure 4 to Figure 6, respectively.

Table 1. Symmetric components of the current

Parameter	Prefault (A)	Post fault (A)
PV inverter 1		
Positive sequence	22.705	23.153
Negative sequence	0	-0.0572
Zero sequence	0	0.0106
PV inverter 2		
Positive sequence	2.4455	2.5438
Negative sequence	0	-0.058
Zero sequence	0	0.0107
PV inverter 3		
Positive sequence	2.4455	2.5438
Negative sequence	0	-0.058
Zero sequence	0	0.0107

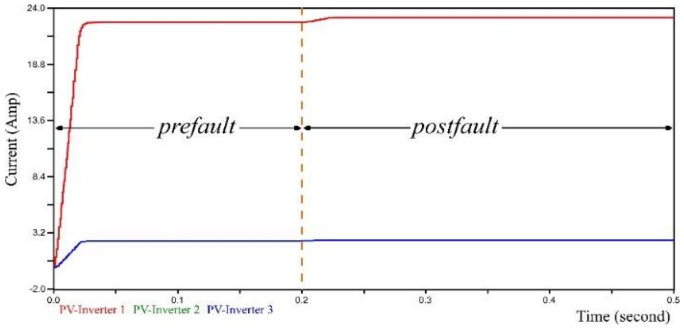

Figure 4. PV inverter positive sequence current curve

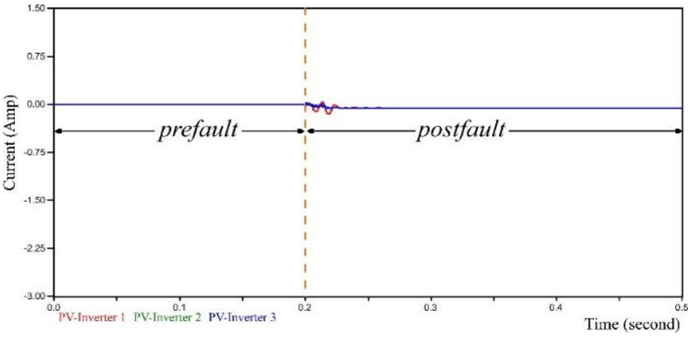

Figure 5. PV inverter negative sequence current curve

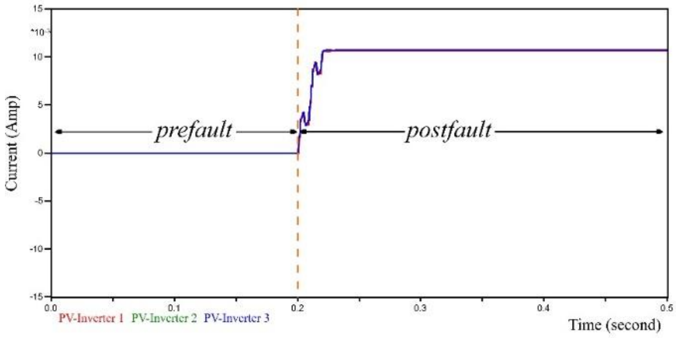

Figure 6. PV inverter zero sequence current curve

3.2. Symmetrical component of the voltage

The complete tabulation conclusion of the simulation voltage value for a single-phase fault is shown in Table 2. The simulation results show that the positive sequence current value before the fault occurs for inverter 1 is 16.326 V, PV inverter 2 and PV inverter 3 is 16.332 V. After the sequence current fault occurs, positive PV inverter 1 decrease to 15.959 V, and 16.054 V. Meanwhile, all PV Inverters showed a negative sequence current value of 0 for negative sequence current. After a disturbance, the negative sequence current of PV inverter 1 was 575.35 V and -579.16 V for PV inverter 2 and 3. Zero sequence current before fault occurs is 0 A for all PV inverters. After a disturbance, the zero sequence current from PV inverter 1 is -106.42 V and -107.05 for the zero sequence current of PV inverter 2 and 3. The simulation results showing the zero, positive and negative sequence current values are shown in Figure 7 to Figure 9, respectively.

Simulation results of single-phase short-circuit faults with high fault resistance show that the negative sequence and zero sequence voltages experience changes in value at detectable levels. This situation will be used to continue research on developing protection schemes for distribution networks connected to PV inverters. In this way the reliability of the system connected to the DG can be increased.

Table 2. Symmetric components of the voltage

Parameter	Prefault (V)	Post fault (V)
PV inverter 1		
Positive sequence	16.236	15.959
Negative sequence	0	575.35
Zero sequence	0	-106.42
PV inverter 2		
Positive sequence	16.332	16.054
Negative sequence	0	579.16
Zero sequence	0	-107.05
PV inverter 3		
Positive sequence	16.332	16.054
Negative sequence	0	579.16
Zero sequence	0	-107.05

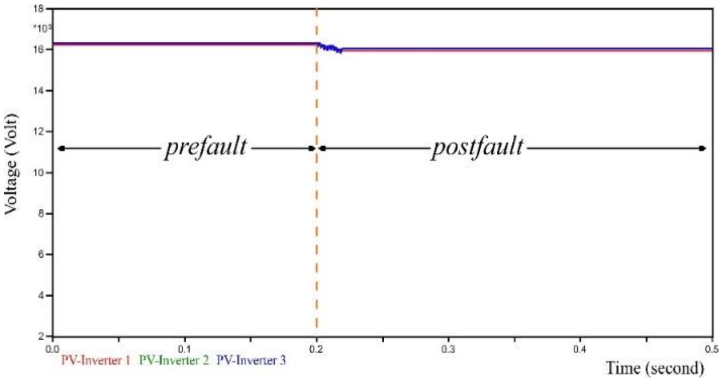

Figure 7. PV inverter positive sequence voltage curve

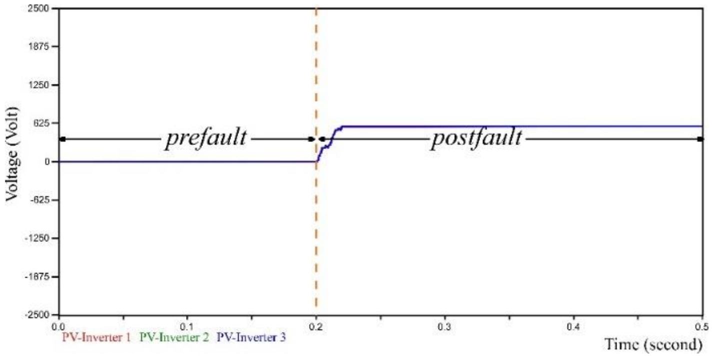

Figure 8. PV inverter negative sequence voltage curve

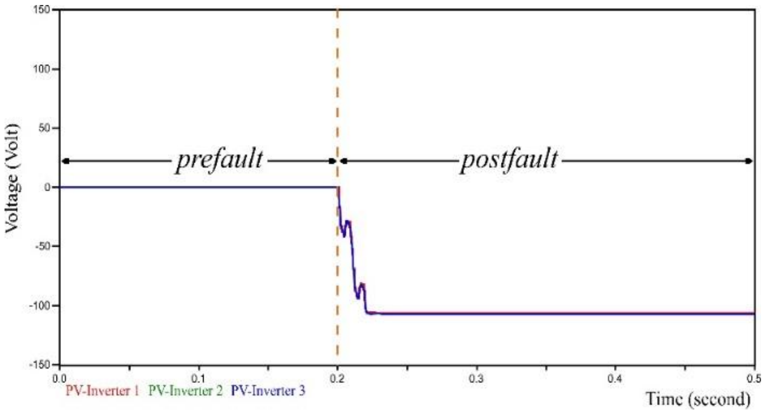

Figure 9. PV inverter zero sequence voltage curve

4. CONCLUSION

The ATPDraw-EMTP model for IEC microgrid system connected to a PV inverter, modelled as SOGI-FLL, has provided an overview of the symmetric components of the fault current and PV inverter voltage. Short-circuit fault is simulated at 200 ms. The overall duration of the simulation is 500 ms. The simulation results show that only positive sequence components appear before the disturbance occurs, both for current and voltage symmetric components. After a disturbance occurs, the symmetric components of the current do not show a large increase. The same condition also applies to the positive sequence voltage which experiences a small decrease. In contrast to negative sequence and zero sequence voltages, the changes that occur are very significant. Before the disturbance occurred, the values of these two parameters were zero, but after the disturbance occurred, the values of these two parameters experienced a drastic decrease. This condition shows that the negative sequence and zero sequence voltage can be utilized to continue research on protection schemes in distribution networks connected to PV inverters.

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