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IMICV fault analysis method with multiple PV grid-connected inverters for distribution systems

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ABSTRACT

A novel faults analysis method with multiple PV grid-connected inverters for distribution systems is proposed. The aforesaid proposed method Inverter Matrix Impedance Current Vector (IMICV) employs symmetrical components combined with a matrix denominated of Inverter Matrix Impedance and with a vector denominated Impedance-Current Vector which are formed by inspection. This matrix and this vector are used to solve a linear system of equations where the following post-fault variables are: current in substation, the voltage at the fault point and voltages in the PV grid-connected nodes. A comparison of results obtained using the new method with the results of the professional software ANAFAS validates the method proposed. Computer simulations show that the proposed method for classical shunt faults analysis is efficient, accurate and easy to program.

1. Introduction

The system of symmetrical components is used traditionally for the analysis of symmetrical and asymmetrical operation of distribution systems. Faults in general and short-circuit currents in particular are the most severe operating conditions in distribution systems. Each of the different faults, e.g., single-line-to-ground (LG), line-to-line (LL), line-to-line-to-ground (LLG) and three-phase (LLL) can be represented by an equivalent circuit diagram in the system of phase components and by this in the system of symmetrical components as well [1–3].

Over the last years energy shortage and environmental problems have been increasing seriously. Thus, humanity must adopt renewable energy and green energy in order to achieve a sustainable development.

Since creation of Czochralski process to make the first generation of single-crystal silicon photovoltaic, the photovoltaic (PV) systems have been utilized as renewable energy sources to produce electric power [4]. It is worth noting that PV power is becoming cheaper and cheaper every year, as a result it is expected to have a higher penetration level in power networks. Grid-connection of PV systems is accomplished through the inverter, which converts dc power generated from PV modules to ac power used for ordinary electric equipments power supply.

Since growth of PV systems accelerates, it has become important as the PV systems will contribute to the fault current during a fault. Several studies investigate the impact of a PV on the fault current levels on a feeder using mainly time domain simulation methods [5]. The following can be cited: Plet and Green proposed inverter fault models and their use in a network fault analysis [6]. Moreover, in [7], a novel unsymmetrical faults analysis method with hybrid compensation for microgrid distribution systems is proposed. This method employs the actual three-phase models to handle unsymmetrical faults. In [8], a fault analysis method for inverter-interfaced DGs was proposed. The method aims to estimate the initial high current that an inverter interfaced DG under voltage control scheme can inject during the first cycle of the

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fault. Ref. [9] proposed a methodology to establish a general index focused on the insertion of distributed photovoltaic generation and energy storage using batteries. Ting-Chia Ou proposed a direct building algorithm for microgrid distribution ground fault analysis [10]. In [11], MATLAB/SIMULINK is used to simulate single phase and three phase voltage source inverters which are increasingly being used to integrate electric power generation from solar photovoltaic with the electric distribution systems. Ref. [12], also used MATLAB/SIMULINK to present a model of grid-connected hybrid AC/DC microgrid. Furthermore, dynamic models for each system component are developed and used for short-time transient simulations. In [13], a PV inverter dynamic model in PSCAD/EMTDC is developed. In [14], the authors investigated the impacts of PV connection on the protection systems of a distribution network, especially when power flow is reversed in high penetration scenarios. Even though the substation model was built in a real-time EMTP type simulation environment using RTDS/RSCAD. However, the power system literature does not present a simple method, which can be used in real time. This method is based on solving a linear system inside an iterative process, meanwhile it calculates the fault current (on frequency domain) on radial distribution system connected with multiple PV generation.

In the Power Engineering and for the electric power industry real-time fault analysis is oriented toward applications in the distribution system operation area other than the planning analysis. The results of these earlier studies can be used for distribution adaptive relay coordination and settings when feeder reconfiguration is performed, which could be a useful future smart grid application [15].

This paper proposes a single and efficient method to calculate shunt fault current on a PV-dominated distribution feeder. The novel faults analysis method employs symmetrical components combined with a matrix denominated of inverter matrix impedance (IMI) and with a vector denominated impedance-current vector (ICV) which are formed by inspection. The proposed method is denominated Inverter Matrix Impedance Current Vector (IMICV).

The paper is organized as follows: Firstly, the photovoltaic system model is introduced. Secondly, a complete demonstration of the new method is presented, including a numerical example. In fourth section the new method is validated. Final conclusions and references are contained in this paper as well.

2. Model of the photovoltaic system

According to German standard VDE 4105 reducing the power factor (PF) of PV generation using fixed PF should be taken, whether inductive or capacitive, aimed at improving the operation of the PV system by the distribution network. Thus, a complete model for a PV system must represent active and reactive current components.

When a fault occurs on the feeder, the PV system feeds current to the fault. Due to the characteristics of the inverter, the fault current has only positive sequence component which depends on the PV inverter design. Since the PV systems are designed to push the maximum power available from PV panels to the system, the PV inverter tries to push this power even under low voltage conditions which occur during a fault, i.e., it will try to act like a constant power source [5]. Hence, the current injection from a PV inverter to the system can be approximated as in Eq. (1):

$$I_{\text{post-fault}(+)} = \frac{P_0}{|V_{\text{post-fault}(+)}|PF} < (\text{angle}(V_{\text{post-fault}(+)}) - \arccos(PF)) \quad (1)$$

where P_0 is the power from the PV panels, $V_{\text{postfault}(+)}$ is the ac terminal positive sequence post-fault voltage and arccos(PF) is the arc cosine of the power factor.

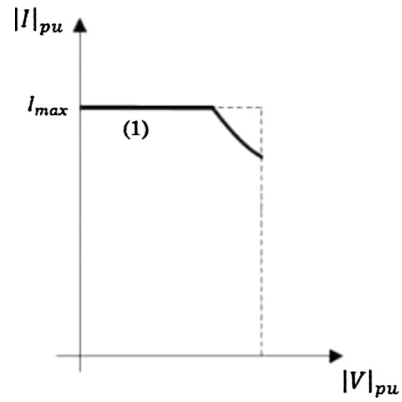

Fig. 1. V–I characteristics of a PV system.

However, if this current gets to be higher than the maximum current rating of the inverter, it will limit the current at its maximum level as shown in Eq. (2). Inverters limit their current to one to two times the rated current [5].

$$I_{\text{post-fault}(+)} = |I_{\text{max-inverter}}| < (\text{angle}(V_{\text{post-fault}(+)}) - \arccos(PF)) \quad (2)$$

The V–I characteristics of a PV system is showed in Fig. 1.

According to Fig. 1, the PV system feeds current to the fault. If the three phase voltages are above of the nominal voltage, the magnitude of the injected current will be calculated so as to maintain the initial active power. I.e. the current is calculated by the Eq. (1). If the voltage gets too low, the magnitude of the current will reach its maximum limit ($I_{\max}$) and it will not pass this value. The horizontal segment (1) in Fig. 1 presents this situation.

3. New method formulation

A complete demonstration of the IMICV method is presented hereafter, illustrated with a numerical example.

One of the most powerful matrices used in power system analysis is the bus impedance matrix (Z-Matrix). The Z-Matrix is generally full, i.e. it contains elements in every position unless there are disconnected parts of the network. Generally, an algorithm for finding the Z-Matrix is more direct and cheaper to implement than performing an inversion of admittance matrix [1].

The new method employs positive, negative and zero sequences components combined with the IMI and with ICV.

Initially, the proposed method requires the formation of the classical positive Z-Matrix and classical zero Z-Matrix [16] which are demanded to calculate the post-fault voltages.

The iterative process requires the setup of the post-fault voltages. Then, initial post-fault positive sequence voltages are calculated using the equations to follow:

LL fault

$$v_{i_+}^r = 1 - \frac{z_{i,k}}{2(z_{k,k})} \quad (3)$$

LG fault

$$v_{i_+}^r = 1 - \frac{z_{i,k}}{2(z_{k,k}) + z_{k,k}^0 + 3z_g} \quad (4)$$

LLG fault

$$v_{i_+}^r = 1 - \frac{z_{i,k}}{z_{k,k} + (((z_{k,k})(z_{k,k}^0 + 3z_g))/(z_{k,k} + z_{k,k}^0 + 3z_g))} \quad (5)$$

LLL fault

$$v_{i_+}^r = 1 - \frac{z_{i,k}}{z_{k,k}} \quad (6)$$