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Fault analysis of unbalanced radial and meshed distribution system with inverter based distributed generation (IBDG)

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ABSTRACT

The fault current contribution of inverter based DGs (IBDGs) may affect the operation of protective devices present in the system. Hence, it is necessary to consider the presence of IBDGs in short-circuit analysis of distribution system. A short-circuit analysis approach for unbalanced distribution system with IBDG, incorporating different voltage dependent control modes, is proposed in this paper. Comparison of the results obtained by the proposed method with those obtained by the time domain simulation studies carried out using PSCAD/EMTDC software, shows the accuracy of the proposed technique.

1. Introduction

Integration of distributed generation (DG) to the grid improves the system efficiency (by improving the system voltage profile) and reliability. The DGs deliver electrical energy with low carbon emission and also help to reduce the feeder loading. Generally, inverter based DGs (IBDGs) such as, fuel cell, wind power, photovoltaic, micro-turbines etc. are used in the distribution system. However, integration of a DG to a distribution system increases the fault level of the system as it contributes to the fault current during a fault. A single small DG unit may not contribute much to the fault current, but the contributions of many small units may cause malfunctioning of protective devices due to increased fault current [1,2]. To overcome the above discussed problem, two schemes have been proposed in the literature. The first scheme recommends the disconnection of all the DGs present in the system during faults before the operation of protective devices [3], while the second scheme proposes to restrict the fault current contribution from DGs to a safer value, so that all the protective devices present in the system function properly [4–11]. This can be achieved by incorporating a control strategy in the inverter of the IBDGs to limit its current during fault conditions. First scheme has a drawback that for every sustained as well as temporary fault, all DGs will be first disconnected from the grid and subsequently would be synchronized with the grid after fault clearance. Disconnection of DGs also causes a voltage dip in the system. Hence, the second scheme is preferred nowadays.

In [4–11], for considering the IBDGs in fault analysis, an IBDG has been modeled in sequence component frame to operate the inverter in current control mode. The current controlled inverter model is based on *dq*-0 control schemes. In this scheme, the phase components of the inverter current from IBDG are first converted into *dq*-0 components and a control scheme is provided for controlling these *dq*-0 components. The effectiveness of these control techniques have been demonstrated through time-domain simulation studies carried out on MATLAB/SIMULINK environment [12]. In [13], an experimental setup for fault analysis with *dq*-0 control scheme for inverter has been implemented. In [14,15] a short-circuit analysis method with micro turbine generation (MTG) system has been proposed, for both islanded and grid connected mode. This method is based on two matrices; BIBC (Bus injection to branch current) and BCBV (Branch current to bus voltage) [16]. A fault analysis method with multiple grid connected photovoltaic (PV) inverters has been developed in [17] which utilizes symmetrical component of impedances. This method is based on a matrix denominated as Inverter Matrix Impedance (IMI) and a vector denominated as Impedance-Current Vector (ICV).

In the literature, some of the fault analysis methods of distribution system with IBDGs [4–11] are based on sequence component approach and on time domain simulation studies. However, sequence component based fault analysis methods are not suitable for unbalanced distribution network with single and two phase lines, and for distribution lines with unequal mutual impedances, as sequence components can not be decoupled for unbalanced

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systems [18]. Also, these techniques have been applied to the fault analysis of small size distribution system only. On the other hand, the analytical methods available in the literature [14,15,17] for short-circuit analysis of distribution system with IBDGs have not considered the loads during short-circuit calculations. In this paper, an analytical approach for the short-circuit analysis of a distribution system with IBDG is proposed that includes different types of loads during short-circuit analysis. The results obtained by the proposed technique have also been compared with those obtained by time domain simulation studies carried out by the PSCAD/EMTDC [19] software.

The remainder of this paper contains three sections. Section-II describes the proposed short-circuit analysis method in detail for different unsymmetrical short-circuit faults. In Section-III, test results obtained by the proposed method for various types of faults and also for multiple faults in modified IEEE-123 bus radial as well as weakly meshed distribution networks are discussed. Section-IV concludes the paper.

2. Short circuit analysis with IBDG

2.1. System modeling with IBDG

In this work, it is assumed that the IBDGs are operating at unity power factor under normal operating conditions. Further, it is also assumed that the IBDGs operate in zero power factor (leading) under fault conditions [9,11] to deliver reactive power to the system (to improve the system voltage profile during the fault). The short-circuit current contribution by the IBDG is limited to the short-circuit current capacity of the switching devices (I_{sc}^{inv}), by operating the inverter in a constant current mode [9,11]. The three phase inverter, with separate control scheme for each phase, is used to integrate the DG with the grid through a step down transformer.

Let us consider an unbalanced distribution system with an IBDG connected to the *n*th bus of the system through a step down transformer, as shown in Fig. 1. The distribution system is assumed to have u three phase, v two phase, and w single phase buses. It is assumed that the total No. of loads (balanced as well as unbalanced) connected to the system is *nld*. Two different types of loads have been considered in this work: constant power and voltage dependent loads. The polynomial voltage dependent load model (*ZIP* model) [20] is described by Eqs. (1a) and (1b) as

$$\frac{P(V)}{P_o} = F_Z\left(\frac{V}{V_o}\right)^2 + F_I\left(\frac{V}{V_o}\right) + F_P \tag{1a}$$

$$\frac{Q(V)}{Q_o} = F'_Z\left(\frac{V}{V_o}\right)^2 + F'_I\left(\frac{V}{V_o}\right) + F'_P \tag{1b}$$

where P and Q are the active and reactive load power, respectively, and V is the magnitude of the terminal voltage. V_o, P_o and Q_o are the nominal values of voltage, active and reactive power, respectively. F and F' are the fractional constants, and the subscripts Z, I and P belong to the contributions of constant impedance, constant current and constant power loads, respectively. The pre-fault bus voltages of the unbalanced distribution network (Fig. 1) are calculated using distribution system load flow (DSLF) [16]. In DSLF, IBDG is considered to inject a complex power S_{dg}^{p} at each phase 'p' of the inverter bus under normal operating conditions where $S_{dg}^{p} = P_{dg}^{p} + j0.0; p = a, b, c; P_{dg}^{p}$ denoting the real power injected by IBDG at phase 'p'. In each iteration of DSLF, the load power consumed by the voltage dependent loads is updated using Eq. (1). The pre-fault inverter current is then calculated using the values of bus voltages obtained from DSLF as

$$\bar{\mathbf{I}}_{\mathbf{inv}}^{\mathbf{abc}} = \left[\bar{\mathbf{z}}_{\mathbf{t}}^{\mathbf{abc}}\right]^{-1}\left(\bar{\mathbf{V}}_{\mathbf{inv,st}}^{\mathbf{abc}} - \bar{\mathbf{V}}_{\mathbf{n}}^{\mathbf{abc}}\right) \tag{2}$$

where $\bar{\mathbf{I}}_{\mathbf{inv}}^{\mathbf{abc}} = \left[\bar{I}_{inv}^{a} \quad \bar{I}_{inv}^{b} \quad \bar{I}_{inv}^{c}\right]^T; \left[\bar{\mathbf{z}}_{\mathbf{t}}^{\mathbf{abc}}\right] = \begin{bmatrix} \bar{z}_t^{aa} & \bar{z}_t^{ab} & \bar{z}_t^{ac} \\ \bar{z}_t^{ba} & \bar{z}_t^{bb} & \bar{z}_t^{bc} \\ \bar{z}_t^{ca} & \bar{z}_t^{cb} & \bar{z}_t^{cc} \end{bmatrix}$ is the transformer impedance matrix. $\bar{\mathbf{V}}_{\mathbf{inv,st}}^{\mathbf{abc}}$ and $\bar{\mathbf{V}}_{\mathbf{n}}^{\mathbf{abc}}$ are the 3-phase voltage vectors of the inverter bus and *n*th bus, obtained from the load flow solutions, respectively. Next, all the loads are converted to constant impedance loads using pre-fault DSLF solution. Now, KCL equations are written for all the buses of the system except IBDG bus and substation bus. These KCL equations can then be expressed in the matrix form as [21]

$$[\mathbf{Y_{bus}}][\mathbf{V}] = [\mathbf{I}] \tag{3}$$

The details of the bus admittance matrix $[\mathbf{Y_{bus}}]$, bus voltage vector $[\mathbf{V}]$ and source current injection vector comprising of substation injected current $[\mathbf{I}]$ are given in [21] and hence not repeated here. The sizes of the $[\mathbf{Y_{bus}}]$ matrix, $[\mathbf{V}]$ and $[\mathbf{I}]$ vectors for an unbalanced distribution system having u three phase, v two phase, and w single phase buses, are $((3u + 2v + w) - 3) \times ((3u + 2v + w) - 3)$, $((3u + 2v + w) - 3) \times 1$ and $((3u + 2v + w) - 3) \times 1$, respectively [21]. Now, if an IBDG is connected at *n*th bus of the system, only the elements of $[\mathbf{Y_{bus}}]$ matrix corresponding to bus '*n*' (location of IBDG) will be modified as

$$\bar{\mathbf{Y}}_{\mathbf{nn}}^{\mathbf{abc}} = \bar{\mathbf{Y}}_{\mathbf{nn}}^{\mathbf{abc}} + \bar{\mathbf{y}}_{\mathbf{t}}^{\mathbf{abc}} \tag{4}$$

where, $\bar{\mathbf{y}}_{\mathbf{t}}^{\mathbf{abc}} = \left[\bar{\mathbf{z}}_{\mathbf{t}}^{\mathbf{abc}}\right]^{-1}$ and $\bar{\mathbf{Y}}_{\mathbf{nn}}^{\mathbf{abc}}$ is the (3×3) submatrix (corresponding to bus '*n*') of the $[\mathbf{Y_{bus}}]$ matrix [21]. The source current injection vector $[\mathbf{I}]$ will also be modified to $[\mathbf{I_m}]$ (comprising of both the substation injected current and the current injected by the IBDGs), and is given as

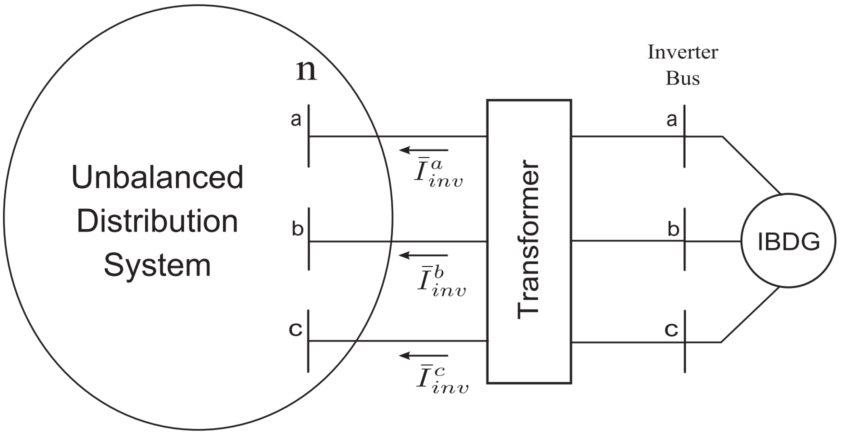

Fig. 1. An unbalanced distribution system with inverter based DG (IBDG).