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# Ground fault current analysis with a direct building algorithm for microgrid distribution

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ABSTRACT

A direct building algorithm for microgrid distribution ground fault (MGDGF) analysis is proposed in this paper. Four possibilities of the network topology changes were considered with the proposed iterative process for ground fault analysis. This paper also discusses the ground fault model of a battery energy storage system (BESS) as a distributed energy resource (DER), which can be used for both islanded and grid-connected modes. The proposed algorithm is robust and accurate. Test results demonstrate the potential of the proposed algorithm in MGDGF applications.



## 1. Introduction

A microgrid (MG) is made up of large numbers of on-site distributed energy resources (DERs), which may include battery energy storage systems (BESSs), solar cells, microturbine generations (MTGs), small hydel, diesel engines, wind energy conversion systems, and fuel cells [1–6]. The MG is expected to increase the use of renewable energy, and thus reduce $CO_2$ emissions. The MG distribution (MGD) power flow is a very important tool for improving the reliability and efficiency of fault analysis, and is used for operational as well as planning purposes in MGD management (MGDM). Network optimization, feeder switching, MG operation, and many other applications re quire a robust and efficient power flow method [7–10]. Real-time fault analysis is oriented toward applications in the MG 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. Several power flow algorithms specially designed for distribution systems have been proposed in the literatures [11–21].

Gauss–Seidel and Newton–Raphson (NR) based algorithms are two commonly used techniques in the industry for power-flow solutions. The NR algorithm has been used primarily in Energy Management Systems (EMS), especially the fast-decoupled version which tends to exceed other techniques in terms of performance [11]. However, some features cause the traditional power flow methods used in power systems, such as the Gauss–Seidel and Newton–Raphson techniques, to fail in distribution applications, such as the multiphase and unbalanced network, radial or weakly meshed structures, large number of branches and nodes, high resistance to reactance ratios, wide-ranging resistance and reactance values. In particular, the assumptions necessary for the simplifications used in the standard fast-decoupled Newton–Raphson method [11] are not necessarily true in other distribution systems. This research will design a computer algorithm and program that meet the requirements of rigorous operational-type power flow and contingency analyses for an MGD.

One of the most powerful matrices used in power system analysis is the bus impedance matrix *Z*. Despite the importance of the *Z*-Matrix, its usefulness has been constrained by the building process. The *Z*-Matrix is preferred for limited short circuit analysis with perfectly transposed transmission lines, where short circuit analysis may be performed by using the sequence network with zero, positive and negative sequences. The elements of the *Z*-Matrix related to the monitored contingent lines are often used in combination with pre-contingency load flow to determine the net current change after the switching operation. Traditional building algorithms in [22–26] only provide the information about the relationship between the bus voltage and bus current injection. However, applications of the *Z*-Matrix analysis might require data on the relationships among the branch current, bus voltage, and bus current injection. Many techniques have been proposed to modify the traditional *Z*-Matrix building algorithms [25]. Among these, the Gauss implicit *Z*-Matrix method [15] is the most generally used, however, although it does not take advantage of the radial and weakly meshed network structure of distribution systems,

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and requires the solution of a set of equations whose dimensions are proportional to the number of buses. Many studies provided new ideas on how to treat the special topology of distribution systems [18–21].

A compensation-based technique has been proposed to solve distribution power flow problems [18], while an iterative-compensation method which uses the bus admittance matrix to simulate the fault conditions has also been presented [16], [17]. Since the forward/backward sweep technique is widely accepted in the solution process of compensation-based algorithms, new data formats and search procedures are essential, which focus on modeling unbalanced loads and DERs [20]. However, one of the inconveniences of the compensation-based methods is the need for databases which have to be built and maintained.

This paper developed an algorithm which takes advantage of the topological characteristics of distribution systems, and can solve the MGD ground fault (MGDGF) problem directly. This work proposes a ground fault analysis method based on the actual three-phase models and the boundary conditions to completely expand the MGD network characteristics. Two relationship matrices: $\mathbf{B}_I$ and $\mathbf{Z}_{V\text{-}BC}$, the bus injection to branch current matrix and the branch current to bus voltage mismatch matrix, respectively, which are built from the topological characteristics of MGD networks, are used to achieve the MGDGF solutions. The new method is systematic, effective, and easily programmable. The time-consuming LU decomposition and forward/backward substitution of the Jacobian matrix or the *Y* admittance matrix, required in the traditional *Z*-Matrix building algorithms, is not needed in this new approach. Through this algorithm, $\mathbf{B}_I$ and $\mathbf{Z}_{V\text{-}BC}$ can be derived directly and stored no matter how the network expands, and fault current analysis [27–29] can be conducted effectively.

## 2. Unbalanced network model

A three-phase line section model between bus *0* and *k* is shown in Fig. 1. The line parameters can be obtained from the method developed by Carson and Lewis.

A $4 \times 4$ matrix, which takes into account the self and mutual coupling effects of the unbalanced three-phase line section, can be described as

$$[Z_{abcn}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{bmatrix} \tag{1}$$

After Kron's reduction, the matrix dimension will reduce to $3 \times 3$, while the effects of the neutral or ground wire are still included in this model, and (1) can then be rewritten as

$$[Z_{abc}] = \begin{bmatrix} Z'_{aa} & Z'_{ab} & Z'_{ac} \\ Z'_{ba} & Z'_{bb} & Z'_{bc} \\ Z'_{ca} & Z'_{cb} & Z'_{cc} \end{bmatrix} \tag{2}$$

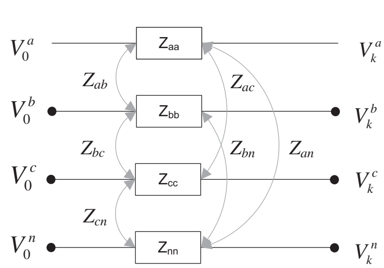


**Fig. 1.** Three-phase line section model.

The relation between bus voltage mismatches and branch currents in Fig. 1 can be expressed as

$$\begin{bmatrix} V_0^a \\ V_0^b \\ V_0^c \end{bmatrix} - \begin{bmatrix} V_k^a \\ V_k^b \\ V_k^c \end{bmatrix} = \begin{bmatrix} Z'_{aa} & Z'_{ab} & Z'_{ac} \\ Z'_{ba} & Z'_{bb} & Z'_{bc} \\ Z'_{ca} & Z'_{cb} & Z'_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{3}$$

For any phases that are not presented, the corresponding row and column in this matrix will contain null-entries. The general form for the voltage mismatches matrix is

$$[\Delta V] = [Z][I] \tag{4}$$

## 3. $\mathbf{B}_I$ and $\mathbf{Z}_{V\text{-}BC}$ matrix

A 5-bus MGD system shown in Fig. 2 is presented as an example. The power injections can be transformed to equivalent current injection (ECI). For bus *i*, the solution at the *k*th iteration for ECI is

$$I_i^{(k)} = \frac{P_i - jQ_i}{\left(V_i^{(k)}\right)^*} \tag{5}$$

where $V_i^k$ and $I_i^k$ are the voltage and the ECI of bus *i* at the *k*th iteration.

The relationship between the bus current injections and branch currents can be described by (6) for the distribution net work. The branch currents $B_i$ can be calculated from the bus current injections as

$$\begin{aligned} B_1 &= I_1 + I_2 + I_3 + I_4 + I_5 \\ B_2 &= I_2 + I_3 + I_4 + I_5 \\ B_3 &= I_3 + I_4 \\ B_4 &= I_4, \quad B_5 = I_5 \end{aligned} \tag{6}$$

Hence, the relationship matrix between the bus current injections and branch currents can be illustrated by

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} \tag{7a}$$

A general form of the matrix can be rewritten as

$$[B] = \mathbf{B}_I[I] \tag{7b}$$

where $\mathbf{B}_I$ is the bus injection to branch current matrix.

The matrix $\mathbf{B}_I$ is an upper triangular matrix and only contains values of 0's and 1's. The relationship between the branch currents and bus voltages of buses 1, 2, and 3 in Fig. 2 can be written as

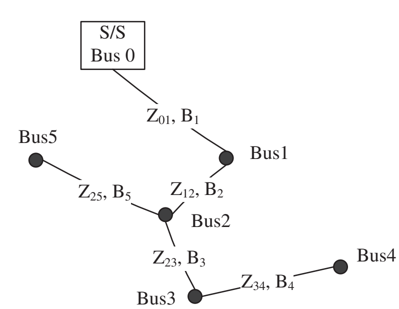


**Fig. 2.** A 5-bus MGD system.