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Efficient network fault analysis method for unbalanced microgrid systems

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ABSTRACT

A novel network short-circuit fault analysis method based on graph theory and a complex short-circuit MVA representation is proposed as an alternative method for unbalanced microgrid systems. The proposed algorithm is based on the branch-path incidence matrix $\mathbf{K}$ and the newly defined augmented incidence matrix $\mathbf{K}_\ell$ of a power network, as opposed to the traditional Z-bus building algorithm and inverse Y-bus matrix with the lower and upper triangular matrix (LU) method. To simplify the unit transformation among different voltage levels, all network components are represented in a short-circuit MVA form with their own infinite bus. Moreover, two major types of distributed generation (DG) models have been successfully implemented using the proposed method; therefore, the contributions of DG to the fault currents can be easily addressed in a microgrid system. The results indicate that the proposed algorithm is accurate and performs better than other methods, particularly with respect to large-scale unbalanced microgrid distribution systems with hybrids of single-, two-, and three-phase.

1. Introduction

With the requirements of low carbon dioxide emission and high utilization of renewable energy resources, many revolutionary developments in power distribution systems have occurred in recent decades. One of the major areas of progress is the development of a microgrid system with hybrid distributed generation (DG) resources: a regionalized, small-scale power network. The DG may utilize renewable energy resources, such as wind, solar, hydrogen, and geothermal sources, or may use fossil energy resources and battery storage [1]. As a result of the presence of the DG in a power distribution network, the distribution network is no longer a passive network. Some advanced techniques and control strategies need to be implemented in a microgrid system [2]. With the increasing penetration of DG, the power distribution system also encounters some technical challenges in the system operation, stability, fault current level, and the difficulty in protection and coordination. To understand well the operational characteristics of the electronically coupled-based DER in a microgrid, centralized/decentralized microgrid control strategies were introduced in [3]. The dynamic operation and control strategies for a microgrid hybrid system with SVC were provided in [4]. A novel intelligent damping controller (NIDC) for STATCOM was proposed to maintain the power quality in a system with various intermittent DG [5]. In [6], several potential conflicts were pointed out between the DG and distribution operation based on the present structure and the protection schemes of typical distribution networks. A procedure for analysing the impact of DG on the distribution system contingency has been reported in [7]. In addition, some protection schemes designed for the islanding operation of a microgrid system with DG have been developed [8]. A network reconfiguration strategy has been proposed to separate a distribution network into a number of autonomous islands with their own DG for power supply [9]. A method to determine the interruption conditions for critical and noncritical loads using the fault information from the upstream network fault calculations are given in [10]. In [11], a protection scheme realized by the fault current limiters and the directional over-current relays, is provided for the protection and coordination of a microgrid system.

For the microgrid protection and coordination, the mentioned protection and coordination schemes are typically based on the results of a precise fault current calculation. Currently, two representative methods are widely implemented in short-circuit fault analysis: (1) symmetrical component-based fault analysis [12] and (2) actual phase-based fault analysis [13–21]. A novel symmetrical component fault analysis method has been proposed to solve a multiphase distribution system in

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Nomenclature

$\mathbf{K}$	branch-path incidence matrices
$\mathbf{K}_\ell$	augmented incidence matrix
$[S_{rated}]$	rated capacity matrix of the component
$[Z_{pu(rated)}]$	per-unit impedance matrix of the component based on its own ratings
MVA_{sc}	component in terms of the complex short-circuit MVA form
$[U_{rated}]$	rated voltage matrix of component
$[Z_\Omega]$	component impedance matrix
$[I_{max}]$	maximum output current matrix
$[C_t]$	ratio of the square of rated voltage and the square of base voltage selected matrix
$[Z''_{\mathbf{d}}]$	sub-transient impedance matrix
$[Z'_{\mathbf{d}}]$	transient impedance matrix
$[Y_{pu}]$	per-unit admittance matrix of the component based on its own ratings
$[S_{base}]$	system base volt-ampere matrix
$[Z\%_{(rated)}]$	percentage impedance of component
$\mathbf{Z}_{Bus}$	bus impedance matrix
$\mathbf{W}_{Bus}$	bus inverse short-circuit MVA matrix
$[I_{rated}]$	rated current matrix
$\bar{I}^{(k)}_{F,inv}$	k-th inverter injection current
$\bar{I}_{Max,inv}$	maximum output current vector
$[Y_{inv}]$	shunt admittance matrix with inverter
$\Delta\bar{V}^{(k)}_{F,inv}$	k-th inverter bus voltage deviation vector
$\Delta\bar{V}^{(k)}_{F}$	k-th bus voltage deviation vector
$[W^F_{Bus}]$	bus inverse short-circuit MVA matrix during a fault
b	number of branches in a distribution system
e	number of elements in a distribution system
n	number of nodes in a distribution system
$f\ell$	number of fictitious links in a distribution system
$r\ell$	number of real links in a distribution system
$\mathbf{C}$	basic loop incidence matrix
$\mathbf{C}_b$	basic loop incidence matrix for the series branches of a distribution network
$\mathbf{U}_\ell$	basic loop incidence matrix for the shunt links of a distribution network
$\bar{i}_\ell$	vector of currents through the links of a distribution network
$\bar{i}_{f\ell}$	vector of currents through the fictitious links
$\bar{i}_{r\ell}$	vector of currents through the real links
$\bar{i}_b$	vector of currents through the branches of a distribution network
$\bar{I}_{Bus}$	vector of bus injected currents
$\bar{I}_{Loop}$	vector of basic loop currents
$\bar{U}_{Bus}$	vector of bus voltages
$\bar{U}_{Loop}$	vector of basic loop voltages
$\mathbf{Z}_{Loop}$	basic loop impedance matrix
$[z_b]$	primitive impedance matrix for branches of a distribution network
$[z_{f\ell}]$	primitive impedance matrix for fictitious links
$[z_{r\ell}]$	primitive impedance matrix for real links
$\bar{u}_{f\ell}$	vector of fictitious links voltages
$\mathbf{W}_{scb}$	series branches matrix in the inverse short-circuit MVA form
$\mathbf{W}_{scr\ell}$	real links matrix in the inverse short-circuit MVA form
Z_f	ground fault impedance

symmetrical components [12]. For the actual phase-based fault analysis, a rigid fault analysis approach with an iterative compensation solution method was proposed in [13]. The paper [14] addresses a new approach for the real-time short-circuit analysis of radially and weakly meshed distribution networks, and uses a hybrid compensation method to account for loops, PV nodes, and fault currents simultaneously. In [15], the balanced nature of power system components and the submatrix solution scheme for the calculation of faulted power systems are discussed. The paper [16] provides a dedicated approach to solve the three-phase load flow and calculate the unbalanced short-circuit current simultaneously for low-voltage systems. An efficient and accurate short-circuit fault-analysis method based on the BIBC and BCBV matrices was proposed for the unbalanced weakly meshed distribution systems in [17]. In [18], two matrices that describe the topological characteristics along with the hybrid compensation techniques were proposed for unbalanced distribution systems. A hybrid-compensation method based on the actual three-phase model was provided for the fault analysis in [19]. A direct building algorithm for microgrid distribution ground fault (MGDGF) analysis is proposed in [20]. This paper also provided a novel iterative process to consider the battery energy storage system (BESS) in distribution ground fault analysis. In [21], a novel inverter matrix impedance current vector (IMICV) fault analysis method considering the detailed PV inverter characteristics is developed for the radial distribution system with multiple PV grid-connected inverters.

Unlike past studies, the proposed method processes the system network structure and component characteristics separately. Herein, the branch-path incidence matrix **K** and the newly defined augmented incidence matrix $\mathbf{K}_\ell$ are used to describe the relations among the network components [22–24]. As microgrid operators execute the reconfiguration of power networks among the radial/weakly looped/meshed constructions, only the incidence matrices need to be changed to meet the corresponding geometric interconnection; the component characteristics matrices are invariant. All matrices utilized in this method are sparse matrices and can be built independently. Therefore, the proposed method is less sensitive to the bus impedance matrix size. Therefore, the proposed method has the advantages of systematic processing, less computation time, ease of learning, and ease of implementation into a computer program. To further simplify the representation of individual component quantities of a microgrid system, the complex short-circuit MVA representation (SCMVAr) method have be applied in the proposed method [25,26]. The SCMVAr method eliminates the need for selecting bases and all the components are represented in terms of their own unique short-circuit MVA value. Hence, the complicated conversion and decimal errors are avoided in the proposed method [27,28]. Therefore, a novel fault-analysis method based on graph theory and a complex short-circuit MVA representation is proposed. The proposed method applies the branch-path incidence matrices, **K** and $\mathbf{K}_\ell$, to form the inverse short-circuit MVA matrix, “**Wbus**” for the fault current calculation. Both incidence matrices can be easily obtained from the input data; subsequently, the “**Wbus**” matrix can be formed in a systematic and straightforward way. Two major types of DG models in the microgrid system have also been successfully combined with the proposed method to evaluate the effects of DGs on the short-circuit fault analysis. To clarify the proposed algorithm, the relationship between the bus impedance matrix, **Z-bus**, and the bus inverse short-circuit MVA matrix, “**Wbus**” are introduced in Section 2. Section 3 introduces the proposed fault-analysis method for an unbalanced microgrid system. Applications and case studies are discussed in Section 4. Finally, a brief conclusion is drawn in Section 5.

2. Relationship between bus impedance matrix and bus inverse short-circuit MVA matrix

This paper proposes a systematic and straightforward fault-analysis method based on graph theory and a complex short-circuit MVA