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Modelling and analysis of delta-connected distribution transformers with symmetrical neutral-grounding structure for microgrid networks

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ABSTRACT

The conventional grounding methods for the delta-connected secondary windings, such as corner grounding and mid-tap grounding, result in unbalanced phase-to-ground voltages. To overcome this issue, the neutral-grounding method can be employed, but when it operates under unbalanced load conditions, the neutral current flowing through the grounding winding may cause overheating and failures. We then propose a symmetrical method for the grounding of three-phase transformer windings, based on neutral grounding of the delta-connected configuration that can help to distribute the neutral currents. In addition, the proposed method provides a multi-voltage solution relevant for microgrid networks, reduces the costs, and makes it more convenient for planning and design. We formulate the mathematical model of a three-phase neutral-grounded transformer bank with three grounding windings based on the nodal admittance matrices and the coupling-free equivalent circuits. A function block of the equivalent circuit of the model is implemented in MATLAB/Simulink and is verified by field testing. The proposed method can provide a reference for engineers for the design and operation of microgrid networks.

1. Introduction

1.1. Background

The social progress and the development of science and technology have increased the demand for electricity, for residential (smart home and building), industrial (automation), and transportation (electric vehicle) use. The availability of electricity and the power quality of the distribution systems may affect the people's livelihood, the commercial operations, and the economic development of a country. It is the task of a power company to build, operate, maintain, and manage the power distribution system in order to attain the reliability of the power supply, rationalize the reserve capacity, and minimize the costs of the power supply and the power shortage [1].

1.2. Literature review

In general, the distribution wiring from power substations can be divided into three-phase three-wire (3ψ3w) and three-phase four-wire (3ψ4w) systems. The three-phase five-wire distribution system (3ψ5w), differing in structure and design of the grounding, has also been studied [2,3]. The main purpose of the system grounding is to stabilize the feeder/line voltages, improve the system safety, and avoid damage to equipment or injury to people [4,5]. The use of an appropriate grounding system can improve the safety and performance of the distribution system and help maintain the intended system performances and power quality.

Power companies typically employ step-down three-phase power distribution transformers (medium-voltage to low-voltage) to provide different voltage levels to the loads. The three-phase distribution transformer powers three-phase loads (such as motors) and single-phase loads (e.g. lighting), and can be connected as wye-delta (Y-Δ), delta-wye (Δ-Y), wye-wye (Y-Y), delta-delta (Δ-Δ), open wye-open delta (U-V), and open delta-open delta (V-V) [6,7]. Each of these connections has its own characteristics and effects on the distribution system [8]. The secondary delta-connection is commonly used in Taiwan's microgrid networks, and its typical grounding methods include ungrounded, corner grounded, and mid-tap grounded. The secondary side of the power distribution transformers must be grounded, in order to improve the safety of the distribution systems. Therefore, it is suitable to analyse the advantages and disadvantages of two traditional grounding methods.

1. Corner grounding method: Fig. 1 shows the schematic and the

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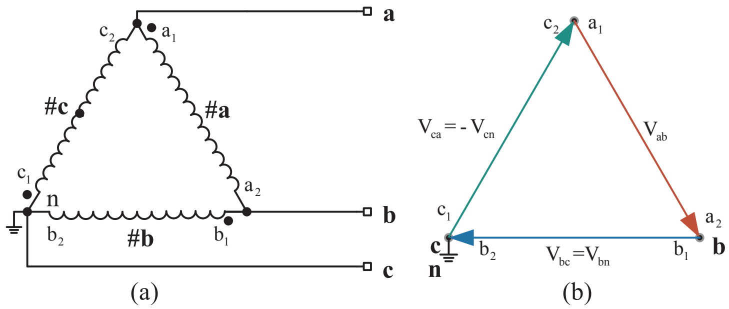

Fig. 1. Corner-grounding method: (a) schematic diagram; (b) voltage phasor diagram.

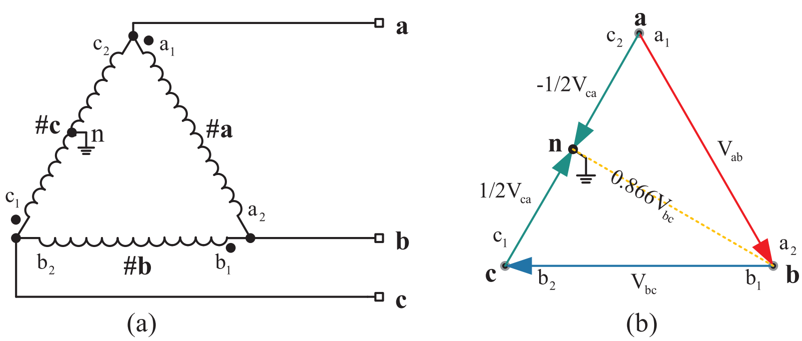

Fig. 2. Mid-tap (centre) grounding method: (a) schematic diagram; (b) voltage phasor diagram.

voltage phase diagram of the corner grounding of a power distribution transformer, where phase C is connected to the ground i.e. to zero potential. It is a simple grounding method, limits the anomalous rise of the potential as well as the isolated third harmonic. Because one phase is connected to the ground, the other two phase-to-ground voltages are equal to the phase-to-phase (line) voltage. This connection is mainly used to power three-phase loads.

2. Mid-tap (centre) grounding method: Fig. 2 shows the schematic and the voltage phase diagram of mid-tap grounding, wherein the 1/2-tap-turn winding of phase C is connected to the ground. This grounding method has the advantage that it can supply power to both three-phase and single-phase loads at the same time. However, its phase-to-ground voltages are unbalanced because (1) two phase-to-ground voltages are 0.5 times the line voltage, while (2) the third phase-to-ground voltage is 0.866 times the line voltage.

In addition, the zig-zag (Z-type) transformer is used for grounding purposes [9,10]. This grounding transformer can solve the absence of the neutral point in △- and Y-type connections. Each phase winding is wound around two magnetic columns so that the zero-sequence flux generated by the two-phase windings can cancel each other. The zero-sequence impedance of the zig-zag type transformer is less than 10 Ω, its no-load loss is low, and it can be used at more than 90% of power rating. Therefore, the Z-type transformer is a good choice as a grounding transformer in traditional methods.

To overcome the described issue of unbalanced phase-to-ground voltages, a neutral-grounding method has been recently proposed for delta-connected transformers that employs a grounding winding and allows to obtain balanced and stable three phase-to-ground voltages [11,12]. Fig. 3 shows the schematic and the voltage phase diagram of this method, wherein phase C is grounded by means of a grounding winding. One end of the grounding winding is connected to a ground point that functions as a neutral point. The other end is connected to a tap on one of the other two-phase windings. The voltage phase difference between the grounding winding and the corresponding phase winding is 180°. It can be shown that all three phase-to-ground voltages are equal, as long as the system remains balanced. This neutral-grounding method for the delta-connected secondary can solve the problem of the three-phase voltage unbalance, but the internal structure of the transformer remains asymmetrical. If the system is operated under heavy and unbalanced load conditions, the neutral current will flow through this grounding winding and can produce overheating and winding failure.

1.3. Aim and contributions

We propose a grounding method based on the neutral grounding concept, which employs three symmetrical grounding windings in a delta-connected secondary, as shown in Fig. 4. Each grounding winding has to withstand one-third of the neutral current under unbalanced load conditions, and therefore, the stability and reliability of the proposed structure are better than those of the neutral grounding via a single grounding winding. Besides, the three grounding windings also make available half the phase-to-ground voltage (see Fig. 4(b)) at their 1/2-tap-turns connection, therefore providing a multi-voltage solution for microgrid networks, such as the ones in Taiwan. The phase-to-phase voltage is of 380 V (a-b, b-c, c-a points) and can power three-phase loads such as electric motors. The phase-to-ground voltage is of 220 V (i.e. a-n, b-n, c-n points), suitable for single-phase loads such as air-conditioners. Furthermore, an additional 110 V voltage is available between the mid-tap connections and the ground (i.e. m_1-n, m_2-n, m_3-n points); it can be used for small electric appliances, thus avoiding the installation of an additional transformer, reducing size and cost of the appliances and simplifying their design.

To determine the characteristics and the system response of a transformer with three grounding windings in a practical distribution system, it is necessary to develop a suitable mathematical model. A proper steady-state model can help optimize the planning, design and operation of the distribution system. Despite the fact that the transformer is a fundamental element in distribution networks, no existing commercial software package provides such a model for even a basic steady-state analysis. Therefore, the purpose of this paper is to develop a steady-state mathematical model (nodal admittance matrices and coupling-free equivalent circuits) of the proposed three-phase transformer with three grounding windings. The function block of the equivalent circuit is implemented by using MATLAB/Simulink software, and the correctness has been verified with field tests. The proposed method can provide a reference for engineers for the design and