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A novel and fast single-phase three-wire power flow solution for a modern home premises wiring systems

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ABSTRACT

Single-phase 2-wire (1φ2w) and single-phase 3-wire (1φ3w) circuit layouts are commonly adopted in premises wiring systems. Compared with 1φ2w circuits, the arrangements of 1φ3w circuits have some advantages such as reduced voltage drop, reduced line loss, and fewer conductors. Currently, more detailed power flow solutions of premises wiring systems are required because they can be used in more applications, such as power loss analysis, conservation voltage regulation (CVR), load balancing, and network reconfiguration especially in the design and operation of modern home energy management systems (HEMSs). This paper presents a novel approach to solve the power flow problem of a 1φ3w premises wiring system. The proposed approach is based on the loop frame of reference rather than the conventional approach, which is normally based on the bus frame of reference. Because the proposed approach is mainly based on graph theory, feeders and branch circuits of a premises wiring system are represented in a more detailed fashion than in previous corresponding mathematical models. In addition, the proposed approach provides an efficient and simple way to help engineers build a performance equation and full-scale system model of a premises wiring system. The simulation results of the proposed approach are verified through the OpenDSS software package and field testing. The proposed approach and implementation technique are of value to engineers and technicians in the design and operation of premises wiring system for dwelling units or smart buildings and may be implemented in HEMSs.

1. Introduction

1.1. Background

Generally, single-phase two-wire (1φ2w) feeders or branch circuits are commonly adopted in premises wiring systems serving lighting and small-appliance loads. The 1φ2w branch circuit is a single-phase branch circuit that consists of one ungrounded conductor and one grounded conductor. The voltage between the ungrounded conductor and the grounded conductor is usually 120 V (110 V in Taiwan). In addition, the single-phase three-wire (1φ3w) branch circuit, a kind of multiwire branch circuit (MWBC), is a single-phase branch circuit that consists of two ungrounded conductors and one grounded conductor (neutral conductor). The voltages between the neutral conductor and two ungrounded conductors are equal in magnitude but out of phase with a 180° phase displacement. The voltage between the two ungrounded conductors is double the voltage between the ungrounded conductor and the grounded conductor. In Taiwan, the 1φ3w branch circuits of a power supply may be derived from a single-phase system (110/220 V) or a three-phase four-wire (3φ4w) delta system. Compared with 1φ2w branch circuits, the arrangements of 1φ3w branch circuits have some advantages such as moderated voltage drops, reduced line loss, and fewer conductors for the same service area in a dwelling unit or building [1].

1.2. Literature reviews

For a 1φ3w branch circuit of a premises wiring system, an efficient and reliable power flow analysis tool must be developed because it can provide vital information and data for an energy management system (EMS) in a smart home or building [2–4]. This information includes node (bus) voltages, branch (line) currents, and active and reactive power flows as well as line losses. In particular, when energy consumption and energy savings are analyzed during the design and planning of a smart home or smart building, the power flow solution is an important technology that should be included.

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Studies of energy consumption analysis and energy-saving design were presented in [5–9]. Al-Ajmi and Hanby [5] presented a building model of a typical Kuwaiti dwelling for implementing an energy consumption analysis. This analysis technique was adopted to achieve building energy savings through proper building design. Neto and Fiorelli [6] presented a comparison between a simple model based on an artificial neural network (ANN) and a model based on physical principles. These are used as auditing and predicting tools to forecast the energy consumption of buildings in Thailand. The analysis results of the industry and commercial buildings show that they are expected to consume approximately 42% of the total energy in Thailand. Cvozdenac et al. [7] created comprehensive data to analyze the total energy consumption in industrial and commercial buildings. Michopoulos and Kyriakis [8] developed an energy analysis tool for a vertical ground source pump system. The analysis tool was verified through a comparison with actual electricity consumption data collected from an existing ground-coupled heat pump. Zhao et al. [9] presented a way to diagnose the energy consumption in a building. The energy consumption of a typical commercial building was analyzed as a case study to introduce their method of evaluating energy consumption.

Existing methods based on a power flow analysis tool can calculate the energy consumption for large systems in an accurate and efficient way; however, these methods should consider the locations and characteristics of each load. Chen and Yang [10–11] presented some ways to make improvements, including a simplified power flow solution to evaluate the annual energy loss for 1φ2w branch circuits of a home or building [10]. However, although this method considered the locations and characteristics of all connected appliances along a branch circuit of a home or building, all node voltages were approximated at 1.0 per unit. Moreover, the researchers in [11] presented a loss factor approach to evaluate the energy loss in 1φ2w branch circuits of a dwelling unit. A practical dwelling unit with two 1φ2w branch circuits was used to investigate the suitability of the loss factor method for evaluating the energy loss of branch circuits.

For a 1φ3w branch circuit of a home or building, many kinds of appliances are connected to the premises wiring system. These appliances include dishwashers, hair dryers, televisions, small fans, and other small appliances. Small electrical appliances are often connected between an ungrounded conductor (phase *a* or *b*) and a neutral conductor. Unfortunately, a simplified power flow solution [10] and a loss factor approach [11] for 1φ2w branch circuits are unsuitable for 1φ3w branch circuit applications in a smart home or building energy management system (HEMS/BEMS). Therefore, power flow solutions for a 1φ3w branch circuit of a premises wiring system are necessary to develop an accurate and efficient power flow analysis tool. This tool will allow for more in-depth study so that the performance of a smart home and its line loss and energy consumption can be evaluated in more detail.

In addition, many researchers are attempting to solve power flow problems efficiently from different viewpoints. In [12–25], the authors introduce conventional power flow solutions for solving an ordinary electrical power system. These conventional power flow methods can be divided into two categories: bus frame of reference and branch frame of reference methods.

(1) In the bus frame of reference method, the bus (node) voltages and bus currents are the main system variables—such as the Z-bus method [12], Newton–Raphson-based algorithm [13–15], and fast decoupled power flow (FDPF)-based algorithm [16,17]—and employ node voltages and currents as state variables.

(2) The branch-based methods, such as the backward/forward sweep-based method [18–24] and loop impedance-based method [25], utilize branch powers and branch currents as state variables.

In addition, the bus-injection to branch-current (BIBC) matrix and the branch-current to bus-voltage (BCBV) matrix were developed to consider the topology of the distribution systems by directly solving the power flow problem instead of using the Newton–Raphson technique [26]. If equivalent current injection or admittance matrices can be obtained for each system component, this method can be applied easily. However, both BIBC and BCBV matrices are based on direct observation, which is awkward for systematized implementation in a power flow program.

Recent studies proposed some new ideas on how to work with network topology characteristics in a distribution system. To solve three-phase power flow problems, these novel methods are based on a branch frame of Ref. [27] or a loop frame of Ref. [28] rather than the conventional bus frame of reference. For the bus frame of reference method, the current injection technique is the most common tool that can be applied to solve unbalanced power flow problems in three-phase distribution systems. However, building the bus admittance/impedance matrices requires a complex procedure.

1.3. Aim and contributions

Given the abovementioned reasons, the objective of this paper is to present a power flow solution method that considers the characteristics of network topology to solve the power flow problems of 1φ3w branch circuits. The proposed power flow algorithm is based on graph theory and a loop frame of reference. The loop impedance matrix $\mathbf{Z_{LOOP}}$ is used as a performance equation for the power flow analysis. Based on graph theory, the $\mathbf{Z_{LOOP}}$ matrix can be obtained from the branch path incidence matrix $\mathbf{K}$. The matrix $\mathbf{K}$ can be built directly by input data and thereby can avoid the complex procedure of the system matrices (bus admittance/impedance matrices). The proposed method is relatively accurate compared with the results of the field tests that verify the correctness of the proposed method. In addition, the proposed method was compared with the OpenDSS software package and it achieved robust convergence performance considering the network topology characteristics of premises wiring systems; it can be applied to large-scale branch circuit premises wiring systems. Therefore, the proposed method can provide engineers with a reference value for the long-term planning of smart homes and buildings as well as real-time power dispatch applications for HEMS and BEMS.

1.4. Paper organization

In this paper, Section 1 briefly introduces the background and objectives of this paper. Some related literature is also reviewed in this section. Section 2 presents the basic concepts of graph theory such as the branch path incidence matrix $\mathbf{K}$ and the basic loop incidence matrix $\mathbf{C}$. The loop impedance matrix $\mathbf{Z_{LOOP}}$ is a technique to solve the power flow problem. Section 3 presents a systematic way to work with the power flow problem of 1φ3w branch circuits. Results and discussions are presented in Sections 4 and 5, respectively. Finally, Section 6 draws a brief conclusion.

2. Problem definition and solution techniques

2.1. Basic graph theory

Graph theory was presented by Leonhard Euler in 1736. Since then, in mathematics and computer science, graph theory has been