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Load-shedding strategy using a zero-sequence power supply scheme for distribution networks in a modern home or building

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ABSTRACT

In this paper, a novel load-shedding technology based on the zero-sequence power supply (ZPS) principle is proposed. The principle is simple to understand, and is based on the symmetric composition method. This technology can rapidly shed loads (three-phase loads and some single-phase loads), which helps in reducing economic losses and equipment costs in the event of a shortage of electricity. The ZPS scheme is based on the selection of one of the three source lines (A-, B-, or C-phase), and then the power is fed to single-phase loads connected between any phases-to-neutral lines. In other words, three-phase and single-phase loads connected between any two-phase lines on the demand side will automatically be shed. In addition, this paper proposes a three-phase distribution transformer with a delta-connected neutral-grounded structure (D_{NGS}). The distribution transformer with a D_{NGS} can provide multi-voltage solutions to supply and meet a variety of loads during the normal power supply (NPS), in order to reduce the additional investment, as well as to simplify design and planning for the distribution networks of a home or building. It can also continuously supply electricity for single-phase loads between phase-to-neutral lines during the ZPS. The proposed method and obtained results are of value to system managers, engineers, and operators, especially the load shedding during power shortages in the distribution networks of a modern home or building.

1. Introduction

1.1. Background

In developing countries, a large electricity demand will be seen in the future. It is necessary to maintain power continuity and reliability, and reduce fault occurrence and imbalance between generated power and load demand leading to system frequency instability. Load shedding (LS) is the ultimate solution for recovering the system frequency, and is the solution for ensuring that the plant supplies power to critical loads. For example, the detailed statistics of South Asia are given in [1–3]. Load shedding is one of the major problems in South Asia, with a total electricity generation of 1211 TW h, of which the total electricity production in Pakistan, India, Bangladesh, Nepal, and Sri Lanka were 97.8 TW h, 1052 TW h, 47.3 TW h, 3.5 TW h, and 11.3 TW h, respectively. The average electricity consumption in Pakistan, India, Bangladesh, Nepal, and Sri Lanka was 78.89 TW h, 864 TW h, 41.52 TW h, 3.23 TW h, and 10.17 TW h, respectively. It can be seen that, despite the large population, the area is unable to produce enough electricity to cope with the requirements of the population. The reasons may be insufficient resources, mismanagement of power systems, and corruption. However, the tariffs in these countries are less than in developed countries. Nevertheless, these shortfalls will result in a devastating effect on the economy, industry, and education [4], along with long-term load shedding [5].

1.2. Literature reviews

The reliable and safe operation of the large-scale power systems is a key target for system operators [6]. Unfortunately, industrial plants are prone to short circuits, power losses, sudden breakdown of distribution lines, and other events. These accidents may cause imbalance between the system and load, which may lead to frequency attenuation, initial power shortage, dangerous cascade effects, or even the shutdown of one or more generators. In other words, power outages will affect utilities, ships, refineries, mines, industrial manufacturing processes, and so on [7].

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One way to reduce the load is through load curtailment, i.e., the LS scheme will act when the sensor detects that the system is in a dangerous state. In order to prevent these events from occurring, an appropriate LS strategy can be adopted to aid in balancing the generated and absorbed power [8,9]. The historical method is to detect a decrease or rise in the frequency of the power system [10]. The threshold value of under-frequency (UF) or over-frequency (OF) is used as a trigger for load or generator shedding, thus maintaining the stability of the power system [11]. Basically, each power system has its own program of the frequency load shedding (FLS). Therefore, the planning and design of an FLS must be reliable, simple, efficient, fast, robust, and properly coordinated with neighbouring power systems [12]. Besides, another way is through load balancing, which means that power suppliers use a variety of technologies to store excess electrical power when low demand period power, and release as demand increasing.

Much literature on optimization and solution technology for load-shedding strategies has been proposed [13–20]. The categories of optimization models include linear programming (LP), nonlinear programs (NLP), and mixed-integer nonlinear programs (MINLP).

Hajdu et al. [13] proposed a computational procedure based on the Newton–Raphson method and the Kuhn–Tucker theorem. El-Abiad et al. [14] proposed a general formulation of the economic dispatch problem that was based on the Lagrange multipliers method. Subramanian et al. [14] proposed a model for sensitivity, and it is used in conjunction with LP for the solution of load shedding problems with a minimum loss of loads. Chan et al. [15] formulated a problem of rescheduling generators and shedding loads in an emergency state. An upper-bounding, sparse LP algorithm was used to solve the linearised scheduling problem. It does not consider the system's frequency, and it can be applied to eliminate overloads in the equipment. Palaniswamy et al. [16] presented a method for optimal load curtailment taking into account generator control effects and voltage and frequency characteristics of loads. The optimization problem was solved by a second-order gradient technique. The proposed model does not deliver a net load shedding and the power balance is obtained through load and generation variations with frequency, which can be insufficient. The aforementioned optimization models were analysed for load shedding corresponding to the static models.

The next is a literature review of dynamic modelling. Rudnick [17] formulated the load shedding problem. The nonlinear optimization model was solved through the Damped Lagrangian Penalty algorithm. The load was modelled considering its voltage frequency characteristic. Shokooh et al. [18] demonstrated the need for a modern load shedding and introduced the new technology of intelligent load shedding. The authors argued that the conventional method of system load shedding is too slow and does not effectively calculate the correct amount of load to be shed. Malekpour et al. [19] developed an approach for the continuous constriction factor particle swarm optimization (CPSO). The results were appealing but the model was not complete, as it did not consider the frequency of the system. Fin Lin et al. [20] formulated an optimal load shedding problem using MINLP solving power flow equations. Frequency, deviation, and reactive power were not considered in the model, which may affect the results. The aforementioned reviews indicated that an accurate optimization model must be presented in order to tackle a load-shedding problem.

The load-shedding technique based on the Lagrangian multiplier concept was widely used in the last few decades. Recently, the shift of load-shedding studies is towards heuristic search techniques, such as genetic algorithms (GAs) [21], particle swarm optimization (PSO) [19], and stochastic algorithms [22,23]. The main reason is that heuristic search technology can solve the problem of large power systems. Another improved load-shedding scheme was introduced in [18]. Shokooh et al. proposed an intelligent load shedding (ILS) technology, which combines system online data, equipment ratings, user-defined control parameters, a knowledge base obtained from offline system simulations, system dependencies, and continually updated dynamic load-shedding tables. Finally, these techniques have their pros and cons. Nonetheless, the implementation of these strategies can decrease the prospect of power system problems and improve the dependability of the energy system.

1.3. Aim and contributions

As noted above, for a variety of reasons, many literature reviews have been used to determine the load-shedding strategy and technology in power systems. However, they all require a complex procedure. Therefore, this paper presents a novel load-shedding technology based on the ZPS scheme that can be used in distribution networks of modern homes and buildings. The principle is simple to understand, according to the symmetric composition method. This technology can rapidly shed loads (three-phase loads and a portion of single-loads), which helps to reduce economic losses and equipment costs in the event of a shortage of electricity. The ZPS scheme is implemented by using one of three source lines (A, B, or C), and then feeds power to any phase-to-neutral line. In other words, three-phase loads and single-phase loads connected to any phase lines on the demand side will be automatically shed during the ZPS. Additionally, the paper proposed a three-phase distribution transformer with a delta-connected neutral-grounded structure (D_{NGS}). The distribution transformer with a D_{NGS} can provide multi-voltage solutions to supply and meet a variety of loads during the normal power supply (NPS), in order to reduce additional investment as well as to simplify design and planning for the distribution networks of a home or building. It can also continuously supply electricity for single-phase loads between the phase-to-neutral lines during the ZPS. The proposed method and obtained results are of value to system managers, engineers, and operators, especially load shedding during the power shortage in distribution networks of a modern home or building.

1.4. Paper organization

The content framework of this paper is divided into five sections. Section 1 is an introduction of this paper, including background, literature reviews, and the aim and contributions. Section 2 describes the basic concept of the novel load shedding in order to help the reader clearly understand the principles of ZPS, in which the configuration of the switch circuit breaker, transformer connection, and the load connection is an important part of implementing the ZPS scheme. Section 3 shows the mathematical model (i.e., a coupling-free equivalent circuit) derivation of the transformer, including eight traditional transformer connections (Types A-H), and a three-phase distribution transformer with a D_{NGS}. The coupling-free equivalent circuit is a commonly used technique for solving the power flow problem of a variety of power networks. In Section 4, the proposed method and model are tested by the benchmark system of IEEE Test Feeder and implement by the MATLAB/Simulink, and then results and discussions are presented. Section 5 draws a brief conclusion.

2. ZPS scheme

2.1. Concepts

Usually, distribution networks (such as typical three-phase four-wire and three-phase three-wire) have sufficient power sup-