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Incorporating customers' reliability requirements and interruption characteristics in service restoration plans for distribution systems

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A B S T R A C T

Due to the serious consequences of system outages on customers and utilities, restoration of the power supply to the healthy out-of-service loads is of profound importance. After faults have been located and isolated, restoration plans are applied in order to maximize the re-energized loads with minimum number of switching operations. The consequences of service interruption depend on the number of affected customers, customer load type and size, time of occurrence, frequency of outages, and the outage duration period. In this work, all these factors have been considered in the restoration process. The constraints involved include voltage limits, line current limits, and radial topology. In addition, an improved encoding which codes the control variables depending on different restoration circumstances is presented. It greatly reduces the number of control variables, filters out a large number of infeasible solutions and improves the algorithm efficiency.

1. Introduction

Faults in distribution systems may cause power supply interruptions to several customers. Distribution systems encounter high frequency of faults caused by several reasons such as weather, component wear and accidents. Therefore, restoration plans are implemented to reduce the outage time caused by faults for achieving better service to customers. Service restoration plan is defined as the determination of the suitable backup feeders and laterals that will enable the transfer of the loads in out-of-service areas through a series of switching operations using normally closed sectionalizes and normally opened tie switches [1].

Customers' requirements for a qualified service are constantly growing. As an example, sensitive customers such as hospitals, traffic signal plants, communication centers, schools and industrial plants are very sensitive to power supply interruptions. Electricity interruptions cause several economic impacts such as loss of production, restart costs, equipment damage, raw material spoilage, the cost of income being postponed, the financial cost of loss market share, and the increased maintenance expenses [2]. Furthermore, electricity interruptions have social impacts such as uncomfortable temperature at work and/or home, loss of leisure time, and risk to health and safety [2].

Due to different types and behaviors of customers, loading levels of distribution systems vary with the time of the day. Consideration of load variation is a key factor in building restoration plans. Authors in Refs. [3,4] arrived at the following conclusions:

- Building a restoration plan using the pre-fault load (i.e., the load level at the time just prior to the occurrence of the fault) may cause overloading in some supporting feeders. Hence, it needs a post-restoration load management using load transfer and/or shedding. This further switching causes a temporary interruption in the transferred loads.
- Building a restoration plan using the daily peak load provides a restoration plan with higher voltage profile, lower branch currents, and lower losses. However, it requires a higher number of switching operations and it may entail unnecessary load shedding.
- Building multiple restoration plans (one for each time unit during the outage period) may require high number of switching operations for further reconfigurations and causes temporary customer interruptions. Further, it is not practical for systems with (MCS) manually controlled switches during short outage periods.

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- Building one overall restoration plan for the whole short outage period with consideration of load variation may avoid all drawbacks of the previous mentioned scenarios.

Different types of customers have different reliability requirements. In reality, customers are concerned only with their ability to use their electrical equipment and the benefits from this use such as production of goods, entertainment, and lights. Customers evaluate the electricity interruptions based on the loss of their usefulness rather than the price which they pay for a unit of electricity or the amount of energy that they consume if the supply is available [5]. Therefore, from the customers' point of view, relying on placing a worth measure value to (ENS) energy not supplied which is the common practice for most utilities is an essential weakness and inappropriate. As a result, utilities should attempt to establish a balance between their benefits and the benefits to their customers through providing service continuity and quality of service economically as possible.

The question here is what items should be considered in the restoration process so that both utility and customers get the maximum benefits.

Although some of the previously published methods have included the effect of load variations on the restoration problem, no attempts have been made thus far to include effects of customers' reliability requirements, time of occurrence, frequency of outages, and the outage duration period on this problem. This work therefore proposes a restoration algorithm that includes consideration of the following:

- The effect of different customers' reliability requirements (i.e., the number of customers, customer load type and size) on service restoration plans
- The effect of interruption characteristics (i.e., time of occurrence, frequency of outages, and the outage duration period) on service restoration plans
- An improved encoding which codes the control variables depending on different restoration circumstances

The effectiveness of the proposed method has been assessed with the use of a test system that has been employed by other researchers published in the literature. The remainder of this paper is organized as follows: Section 2 explains the typical formulation of the restoration problem, Section 3 discusses practical issues related to the service restoration problem, Section 4 discusses important issues related to the practical implementation of the proposed algorithm, Section 5 details the test results, and section 6 presents the conclusions.

2. Typical service restoration problem formulation

The service restoration problem is a multi-objective multi-constraint optimization problem [6]. The problem objectives and constraints are as follows:

2.1. Objective functions

2.1.1. Maximizing the load restored with consideration of load priority

$$\text{Max} \sum_{i=1}^{N_{bus}} w_i * L_i * y_i \tag{1}$$

where N_{bus}: the number of energized buses after service restoration; L_i: load at the ith bus; y_i: status of the load at the ith bus (i.e., equals 1 for a restored load and 0 for an unrestored one); and w_i: priority or importance level of the load at the ith bus.

2.1.2. Minimizing the number of switching operations in order to reduce the required time and the operational cost of the restoration plan

$$\text{Min } SOC = C_{sw} * \sum_{i=1}^{N_s} |x_i - x_{io}| \tag{2}$$

where SOC: cost of switching operations; C_{sw}: cost per switching operation; N_s: the total number of switches; x_i: status of the ith switch in the restored network (i.e., equals 1 for a closed one and 0 for an opened one); and x_{io}: status of the ith switch immediately after the fault has been isolated.

2.2. Constraints

Each closing or opening of a switch creates a new network topology with a new set of voltages, line currents, and active/reactive power balance. Hence, due to the varying topology and the connected loads, bus voltages and line currents change during the restoration process. To obtain satisfactory system operation and to maintain the safety and security of different system components (i.e., transformer and lines), the following constraints are included:

2.2.1. The bus voltages and line currents must be kept within their respective operational limits

These voltage and current constraints make sure that voltages and currents throughout the distribution network will remain within the desired range in the new configuration. This ensures that this new configuration for the proposed restoration plan will not result in an undesired voltage and/or current profile.

$$V_{\min} \le V_{i,t} \le V_{\max} \tag{3}$$

$$I_{j,t} \le I_{\max} \tag{4}$$

where $V_{i,t}$: voltage at ith bus during time interval t, and V_{max}, V_{min}: maximum and minimum acceptable bus voltages (i.e., 0.9 and 1.05 p.u.), and $I_{j,t}$: current in branch j during time interval t, and I_{max}: maximum line current.

2.2.2. Radial network structure should be maintained

The detailed philosophy and technique of applying this constraint is described in Ref. [3].

3. Practical issues related to the service restoration problem

This section highlights important aspects that may improve the operational practices related to the restoration plans.

3.1. Customers' reliability requirements

The cost of electricity interruption is closely related to the way that customers' activities are dependent on electricity. This dependency is a function of both customer characteristics (i.e., customer load type and size) and interruption characteristics (i.e., time and frequency of occurrence, and the outage duration period). Thus, customer characteristics should be considered in building restoration plans as formulated in (1). For comparison purposes,