



Scheme design considering network topology and multi-attribute decision-making for under frequency load shedding



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ABSTRACT

Power system emergency control is one key defense strategy in contingencies for protecting the system from cascading blackout. Under Frequency Load Shedding (UFLS) is one such strategy to ensure system stability by shedding load to retrieve balance between power supply and demand. Novel UFLS scheme design and a scheme optimization approach are proposed in this paper to find the optimal load-shedding schemes for different network partition resulted from contingencies. To obtain all possible UFLS schemes for a certain area, a candidate scheme set design algorithm based on value assigning of scheme parameters is proposed and then a relatively complete candidate scheme set is constructed. Considering network splitting caused by protection, several subsystems may exist from the reconstruction of independent network areas. The concept of homological area is defined and a graph-based method is used to analyse system topology change. Then, a multi-attribute decision-making (MADM) algorithm is introduced for order preference by similarity to an ideal solution (TOPSIS) for global optimizing candidate schemes. Optimal schemes for an area in both isolated area and homological area cases can be derived from all feasible UFLS schemes by MADM method. Simulation results demonstrate that the UFLS schemes can effectively restore system frequency in different network topologies.

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1. Introduction

Power systems have increased greatly in both size and complexity, which increase system vulnerability. Most of the time, systems are operated at the states close to their capacity limits [1], which could decrease system stability margin. The power system can normally operate in the case of small disturbances, such as the simultaneous failure of a double-circuit overhead line. However, sudden loss of large generator or key tie-lines due to line tripping can produce severe generation-load imbalance. The frequency deviation caused by the imbalance may severely harm other generators, load-side equipment, and the system integrity [2].

In the case of a large generation loss, the scheduled power reserve may not be enough to restore system frequency. In such situation, the use of an Under Frequency Load Shedding (UFLS) scheme to curtail load to match generation is well known and established utility practice [3]. UFLS schemes are a last-resort tool to protect the system in case of a severe contingency, shedding an appropriate amount of load for quick recovery of system frequency to its rated value.

UFLS schemes can, according to [4], be categorized into three groups: traditional static UFLS schemes, semi-adaptive UFLS schemes and adaptive UFLS schemes. These schemes continuously measure frequency and optionally the rate of change of frequency (ROCOF) by means of type 81 relays [5]. Static UFLS scheme curtails a constant amount of load, based on experience, at predetermined frequency threshold with intentional time delay. To minimize over-shedding or under-shedding, several shedding steps are contained in static UFLS schemes. The semi-adaptive scheme provides a step forward. It measures ROCOF, df/dt , when a certain frequency threshold is reached. Based on the value of ROCOF, a different amount of load is shed. Measurement of ROCOF is evaluated only at the first frequency threshold. In the following steps, the load is shed in the traditional way. Unlike semi-adaptive UFLS scheme, adaptive UFLS scheme encompasses all intelligent algorithms, trying to figure out the most appropriate response of UFLS protection to a different set of possible system conditions [6]. Reference [7] makes use of the frequency derivative based on the System Frequency Response (SFR) model. Reference [8] uses both frequency and voltage variables to select an appropriate amount of load shedding based on two centralized adaptive load-shedding algorithms. Reference [9] proposes a global load shedding scheme integrated with the rate of frequency decline as an extra variable. Reference [10] describes an approach for obtaining

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a few-seconds-in-advance frequency prediction for WAMS-Based under frequency load shedding.

By analysing historic outages, it is found that systems are likely to be split into several subsystems accompanied by the activation of UFLS relays [11,12]. In such case, there may be one subsystem consisting of several network areas with their own UFLS schemes. These UFLS schemes may influence each other and then the frequency restoration of the whole subsystem if they are not properly coordinated. A new UFLS scheme is proposed for microgrids in [13]. Because the scheme is independent of microgrid parameters, it is not adaptive to parameter variations. A fast and optimal adaptive load shedding method for isolated power systems using Artificial Neural Networks (ANNs) is presented in [14], which performs effective load shedding in various loading scenarios. A novel UFLS adaptive scheme design method based on short-term frequency prediction is proposed in [15]. However, all aforementioned work is based on a single network area, which is regionalized based on administrative or geographical stations via network operation modes. Possible topological change of the system such as network splitting, caused by protection, is not considered. Thus, these schemes may perform well when the network is islanded but fail to restore system frequency when several areas are integrated to a subsystem and could even aggravate the consequence due to the violation of system limits. For example, on November 4, 2006, the Europe interconnected grid experienced a serious incident due to inappropriate operation of UFLS devices' combination [16,17].

In this paper, we propose an improved UFLS scheme design method and the concept of homological area to design UFLS schemes for different system topologies. Based on the attributes of existing static UFLS schemes, a candidate scheme set design method is introduced, which could establish a complete set of candidate shedding schemes. Then, the recombination of electric partitions under various contingencies, especially in system splitting, is investigated. A novel method to find all homological areas of a system is then introduced by studying the bonds of system graphs derived from the dissected sketch map. A multi-attribute decision-making (MADM) algorithm based on TOPSIS (technique for order preference by similarity to an ideal solution) to select desirable schemes is also introduced. Simulation results show that the optimal UFLS scheme obtained by the proposed MADM method could restore the system frequency effectively in both isolated area and homological area cases. The main contributions of this paper are that it proposes: (i) a new UFLS scheme design method to obtain a complete set of candidate schemes for network recovery; (ii) the concept of homological area to obtain the optimal load shedding schemes for various network topologies; (iii) a MADM algorithm based on TOPSIS to find the optimal load shedding schemes in various contingencies.

The remaining parts of this paper are organized as follows. Section 2 describes the attributes of traditional UFLS schemes. In Section 3, candidate set construction for shedding schemes is presented. In Section 4, the concept of homological area for UFLS is described. The method to screen feasible schemes from candidate schemes is presented in Section 5. In Section 6, the multi-attribute characteristics of UFLS schemes are discussed and a MADM algorithm based on TOPSIS is introduced. The proposed MADM algorithm is demonstrated on a practical system in Section 7. Section 8 concludes the paper.

2. Attributes of existing UFLS schemes

Traditional load shedding techniques are still widely used as the most effective UFLS methods because of their simplicity [18]. In these schemes, a fixed amount of load is shed to retrieve

generation-load balance when system frequency falls below predetermined thresholds. At the same time, predefined time delay is determined for each shedding step in order to prevent tripping of UFLS relays during transient cases, such as system oscillation and voltage dip.

For a traditional scheme, four key parameters should be determined: the number of load shedding steps, frequency threshold for each step, total amount of load to be shed, and time delays of UFLS relays. It is complicated to set the magnitude of load curtailment for each step. Traditionally, the total amount of load shed is set based on experience and then distributed to each shedding step with certain algorithms. There are several distribution methods roughly in three categories: equal step-size schemes, incremental step-size schemes and decremental step-size schemes [19].

- For equal step-size UFLS schemes, the amount of load curtailment for each step is $\Delta P_{\Sigma}/N_F$, where ΔP_{Σ} is the total amount of load to be shed and N_F is the number of load-shedding steps in base round.
- For incremental step-size UFLS schemes, load shed for the next step is bigger than that for the current step, which is opposite to decremental step-size schemes.
- Decremental step-size UFLS schemes recover system frequency faster than incremental step-size schemes, while the frequency may rise much higher than the nominal value resulted from over-shedding.

3. Candidate set design for shedding schemes

Four parameters including the number of load shedding steps, frequency thresholds, load shed, and time delays are to be determined for traditional load shedding schemes. Once they are established, a load-shedding scheme is derived.

3.1. Determination of parameters

The number of load-shedding steps contains two parts: base steps N_F and backup steps N_B . From [20] it is seen that N_B , frequency thresholds and the amount of load curtailment of backup rounds are all derived from the base round, and as a result only N_F is an independent variable.

Number of load-shedding steps: Determine the minimum /maximum allowable number of load shedding steps, denoted by $N_{F \min}$ and $N_{F \max}$ respectively. Then, with the step interval ΔN , a sequence of load-shedding steps in ascending order ranging from $N_{F \min}$ to $N_{F \max}$ are obtained. The set for N_F (denoted by Φ_{N_F}) is calculated as follows:

$$\begin{cases} N_F(1) = N_{F \min} \\ N_F(i) = N_F(i-1) + \Delta N; \quad N_{F \min} \leq N_F(i) \leq N_{F \max} \end{cases} \quad (1)$$

Frequency threshold: f_{s1} denotes the frequency threshold of the first step of the UFLS relay. Based on the minimum/maximum f_{s1} (denoted by $f_{s1 \min}/f_{s1 \max}$), the frequency threshold set of the first step (denoted by $\Phi_{f_{s1}}$) can be obtained with given frequency interval Δf_{s1} , which is similar to that of Φ_{N_F} . The difference between two consecutive frequency thresholds is denoted by Δf and the set for Δf (denoted by $\Phi_{\Delta f}$) is obtained in the same way as for Φ_{N_F} after Δf_{\min} and Δf_{\max} are given.

Time delay: Similar to the number of load shedding steps, time delays for a UFLS scheme also contains two parts: base time delay t_F and backup time delay t_B . However, minimum/maximum base time delay and time interval (denoted by $t_{F \min}/t_{F \max}$ and Δt_F respectively) are usually different from those of backup time delay (denoted by $t_{B \min}/t_{B \max}$ and Δt_B respectively). Thus, base and backup time delay sets (denoted by Φ_{t_F} and Φ_{t_B} respectively)

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