Enhancement of Power System Stability Using Adaptive Combinational Load Shedding Methods

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***Abstract*—In the modern power systems operating at lower stability margins, conventional non-adaptive schemes cannot offer adequate protection for securing the power system, especially against combinational events. For major disturbances, the active power deficit is usually accompanied by reactive power deficit and frequency stability and voltage stability of the system are jeopardized simultaneously. In this paper, three adaptive combinational load shedding methods are proposed to improve operation of the conventional underfrequency load shedding scheme in order to enhance power system stability following severe disturbances. The proposed methods use locally measured frequency and voltage signals to counteract such events. In the proposed algorithms, load shedding is started from the locations which have higher voltage decay for longer period of time. The speed, location, and amount of load shedding are changed adaptively depending on the disturbance location, voltage status of the system, and the rate of frequency decline. Operation of the conventional and the proposed load shedding methods have been simulated in an actual large network. Obtained simulation results confirm that the proposed methods provide considerable enhancement in the power system voltage stability margin, and by using the proposed algorithms, various power system blackouts could be prevented.**

***Index Terms*—Adaptive combinational load shedding, rate of frequency decline, underfrequency load shedding, under voltage load shedding, voltage stability margin.**

I. Introduction

POWER system blackouts have become a serious problem for electric utilities, especially in the recent years. This may be in part the consequence of new restrictions imposed by power system deregulation. Due to these limitations, modern power systems are operating at ever-smaller reserve capacity and stability margins. In this situation, traditional entities involved in securing adequate protection and control for the system have become inadequate [1].

The recent system blackouts have occurred due to different forms of system instability, e.g., voltage instability, frequency instability, and combination of voltage and frequency instabilities. To counteract each form of system instability, special protective algorithms have been designed independently in the power systems, e.g., underfrequency load shedding (UFLS) [2] and undervoltage load shedding (UVLS) [3] schemes. One of the major weaknesses of these traditional algorithms is that combination of different forms of instability is not considered in their design, while any one form of instability may not occur in its pure form. This is particularly true in the highly stressed systems and for cascading events [4]. For such events, a group of underfrequency load shedding relays and another group of undervoltage load shedding relays make decisions and operate independently. In this way, an uncoordinated and non-optimal load shedding scenario is performed in the system.

The weaknesses of traditional protection schemes are further revealed for major disturbances of power systems. Major disturbances which lead to system blackouts are usually combinational events involving loss of various generators and transformers and outage of different transmission lines. In such events, frequency decline is usually accompanied with voltage decay and the frequency and voltage stability of the system are jeopardized simultaneously. Voltage decays have been the root cause of several power system blackouts over the past decade [5].

The speed of frequency decline is inherently lower than the speed of voltage decay. Therefore, for some combinational events, fast and severe voltage decays at the system load buses result in reduction of the voltage dependent system loading during frequency decline [6]. Consequently, the amount of frequency decline due to the mismatch between system generation and load is decreased with respect to the condition that the voltage magnitudes of the system buses are in the normal range. This phenomenon prevents the system frequency to fall below the frequency settings of UFLS relays. Therefore, the actual amount of load shed by underfrequency load shedding relays is reduced relative to the required amount. The load shedding may also be delayed in this condition due to the slower frequency decline. The deficiency of conventional load shedding schemes in this condition may result in power system instability and electrical blackout. Examples of this phenomenon have been observed in Italy and North America blackouts [7], [8].

The other problem is that underfrequency load shedding relays might fail to operate correctly when their input voltage decreases considerably from the nominal value. The reason is that underfrequency relays, especially the electromechanical ones, are designed for nominal voltages [9]. As an example, in the 1983 blackout in Sweden, a serious event and its consequent cascade tripping of transmission lines resulted in a very fast drop

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in system frequency and voltage. Underfrequency load shedding relays did not act in this condition and a total blackout occurred in the southern part of Sweden [9], [10].

On the other hand, for some combinational events after initial frequency drop, underfrequency load shedding relays operate and the system frequency returns back to its permissible values. However, the system eventually collapses due to severe voltage declines which result in voltage instability [11]. In fact, following a disturbance such as outage of a power plant or a tie-line, the location of voltage decay and reactive power demand in the system depends on the location of disturbance. However, in the conventional UFLS scheme, locations of the loads to be shed are predefined and independent of location of the disturbance. Since the conventional UFLS scheme does not necessarily shed loads at the area with real or reactive power deficit, there is always a risk of increasing tie line loadings and even voltage instability following the load shedding [12]. This situation occurred exactly in November 1987 in Italy and resulted in the Italian blackout [13]. Load shedding at weak points of the system, i.e., points with greater voltage decay and more reactive power demand, will enhance voltage stability margin of the system. Enhancement of voltage stability margin could help the system to preserve its stability following severe combinational disturbances.

This paper presents several adaptive combinational load shedding algorithms. Unlike the conventional method in which UVLS and UFLS methods are designed separately, in the proposed load shedding algorithms, these two load shedding methods are combined together. The purpose of the proposed algorithms is to enhance the adaptability of load shedding relays and to increase the security of power system during large disturbances by improving system voltage stability margin. In the proposed algorithms during underfrequency condition, loads which have higher voltage decay and for longer period of time are shed sooner. In this way, locations of load shedding become dependent to the location of disturbance and voltage profile of the system. The proposed algorithms use local measured frequency and voltage signals. Therefore, implementation of these methods is much simpler than the centralized load shedding methods which require fast communication links, e.g., [14]–[16].

Performances of the proposed methods are compared with each other and also with the performance of the conventional method. To do this, the methods are tested on the simulated model of an actual large network. Performance of the schemes is evaluated by several simulations in different operating conditions. Distributed and dynamic model of the actual network has been used in the simulations to achieve accurate simulation results. The numerical results demonstrate the effectiveness of the proposed algorithms.

II. Previously Proposed Algorithms

Several algorithms have been proposed in the literature to increase the adaptability of underfrequency load shedding scheme. Many of these algorithms utilize the rate of change of frequency (df/dt) to recognize the required speed and amount of load shedding [17]. In [18] and [19] for large disturbances which result in a high rate of frequency decline, the amount of load shedding is increased. Meanwhile in [20], the frequency settings of the underfrequency relays are increased.

The methods proposed in [14]–[16] use centralized load shedding algorithms and need fast communication of the measured parameters of power system, e.g., the frequency and rate of frequency change of all system generators. Implementation of these methods might become somewhat complicated. In these methods, usually the system voltage status is not considered in the UFLS algorithm and the load shedding locations have been predefined and independent of the disturbance location. Therefore, some of these methods are not robust enough to prevent power system instability following severe combinational events.

In [12], some of the potential weaknesses of UFLS schemes, e.g., improper selection of load shedding locations, are pointed out. The paper proposes a new scheme utilizing frequency and voltage changes to shed loads, specifically in the area where generation has been lost. This method has resulted in lower line loadings and better voltage profiles with respect to the conventional UFLS scheme. However, simulation studies in [21] reveal that shedding loads adjacent to the lost generators does not necessarily lead to lower line loadings for all different networks. Conversely, in some networks, shedding loads distant from system generators provides better results and enhances the voltage stability margins. Moreover, the scheme proposed in [12] requires fast communication of the amount of generation loss, voltage reductions, and the calculated load shedding amount for each bus.

Recently, various researchers have considered the system voltage status in the UFLS algorithms [21]–[25]. In [22] and [23], the effect of voltage variations on the system loads is considered in the system frequency response model. In [24], the loads to be shed are selected based on the magnitude of sub-transmission bus voltages and also static voltage stability margins of the buses. The permissible operating time of load shedding relays and communication delays are major concerns in these centralized methods. In [25], two new local load shedding methods which prioritize low voltage buses in the UFLS algorithm are proposed. It is shown that these methods increase the security of power system following large disturbances and provide higher reactive power margins in comparison to the conventional UFLS scheme.

III. Proposed Adaptive Combinational Load Shedding Methods

In order to improve performance of the conventional UFLS scheme, three adaptive combinational load shedding methods are proposed in this paper. The objective of the proposed methods is to enhance both frequency stability and voltage stability following large disturbances. Enhancement of system voltage stability margin could considerably protect the system against collapse after occurrence of large disturbances.

Following a power system disturbance, the deviation of frequency and voltage quantities are correlated to each other. As such it is more logical to consider combinational load shedding methods which are dependent on both frequency and voltage, instead of designing two independent underfrequency and undervoltage load shed schemes. In the proposed combinational