Electrical Power and Energy Systems 103 (2018) 31–42

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new mechanism for remedial action schemes design in a multi-area power system considering competitive participation of multiple electricity market players

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ARTICLE INFO

Keywords:
Special protection system
Multi-area power system
Multiple electricity markets

ABSTRACT

Unlike to common protective devices that are used for protection of power system equipment, Special Protection System (SPS) means an automated protective system which detects abnormal and predetermined conditions of the power system and applies preplanned corrective actions in order to maintain system integrity. The SPS is widely used in a restructured environment because it is known as a rapid and low cost alternative for network expansion to increase the transfer capability. Although the economic motivations and technical aspects of SPS are proposed in some references, the economic design of an SPS in a restructured environment has received less attention. In this paper, an economic-based method is presented to design remedial action schemes in a Multi-Area Power System (MAPS) with presence of Multiple Electricity Markets (MEM). The innovations of the proposed method are twofold: on one hand, the protection schemes are updated after each electricity market clearing that increases its performance because of the proximity to real time conditions. On the other hand, these remedial actions are designed economically in an environment with several independent Market Operators (MOs) through the interaction with a central coordinator entity. The proposed method is applied on a three-area test system and its results are presented by further explanation of its technical and economic advantages.

1. Introduction

Nowadays, the power systems are normally connected to each other due to different technical, environmental and economic motivations. In spite of different incentives to increase cross-border energy exchange, in some interconnected power systems, security constraints have limited the transfer capability of the tie-lines. In these situations, Special Protection System (SPS) as a low cost and rapid solution has been proposed that provides more and secure exploitation of network capacity [1].

According to the definition of North American Electric Reliability Corporation (NERC), SPS (or Remedial Action Scheme (SPS)) means an automatic protection system designed to detect abnormal or predetermined system conditions, and takes corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. Such action may include changes in demand, generation, or system configuration to maintain system stability, acceptable voltage, or power flows [2]. In a Multi-Area Power System (MAPS), due to the mutual effects of areas actions, the Transmission System Operators (TSOs) should act coordinately in protection schemes points of view. Otherwise, in the case of an event in one area, adjacent areas can be adversely affected and the side effects of this incident can permeate the whole system and endanger its stability [3].

In this context, in some references the issue of load shedding in MAPS has been proposed [4–7]. In [4], an adaptive method of load shedding in a two-area power system with weak interconnection is proposed. According to the proposed method, whenever a generation shedding occurs in the system, the frequency first derivative of each area is initially calculated in a central control center and the area with nonzero frequency change, at the beginning of the event, is detected as the affected area and considered as the highest priority for load shedding. If the load curtailment is required to maintain the total system stability, the load of the affected area is initially dropped and then it comes to the other areas. The same load shedding method is adopted in [5] for a five-area system. In [6], the frequency first derivative criterion is used to determine the candidate area for load shedding too, with the difference that the power deficit is estimated based on the frequency of the center of inertia, instead of the areas frequency because of less deviation. Moreover, for minimizing the amount of shed load, in each step of load shedding, the voltage dependence of load and activated

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https://doi.org/10.1016/j.ijepes.2018.05.018
Received 12 December 2017; Received in revised form 24 February 2018; Accepted 13 May 2018

spinning reserve are considered. In the power systems with automatic Under Frequency Load Shedding (UFLS), the load shedding system disconnects the loads instantly or with a short delay in the case of frequency drop. The numbers of load shedding steps, time settings and amounts of shed load in each step can vary in different power systems. The difference in load shedding method among areas in a multi-area power system may cause under frequency or over frequency in emergency situations. In [7], the frequency behavior of Europe-Russia interconnected power system with different load shedding algorithms in each side of the interconnection is investigated. This paper simulates the load shedding system operation for different scenarios of active power unbalances and concludes that uniform philosophy of load shedding in all areas of an interconnected power system can result in more reliable operation during the emergency situations.

Attention to the technical criteria in SPS design with the purpose of the power system stability is considered in some Refs. [8–34]. Improving the system Voltage Stability Margin (VSM) is one of these technical criteria known as the objective of SPS design [8–14]. In [8], a load shedding scheme is proposed to maintain system voltage stability in the case of predetermined contingencies by using a fuzzy-based multi-objective optimization framework. The objectives are minimizing total load cut, maximizing VSM and improving the integral of the deviation from nominal voltage. In [9], a multi-objective framework is used to determine the event-based remedial action schemes to prevent the frequency and voltage instabilities. The considered objective functions consist of VSM, steady-state frequency deviation, maximum transient frequency deviation and shed load amount. An approach of optimizing the event-driven load shedding against voltage collapse is proposed in [10] that includes candidate buses selection, voltage stability assessment and differential evolution optimization. In [11], a method of SPS design is proposed to mitigate cascaded voltage collapses. In this method, the unstable post-contingency operating point is brought back inside a stable region by adopting the optimal remedial actions that are determined by a sensitivity analysis method. A method of determining the optimal location and amount of load shedding for voltage collapse prevention is presented in [12]. According to the proposed method, the non-linear optimization problem is converted into some linear sub-problems and these linear optimization problems are solved by a multi-stage solution. In [13], the optimal amount of load shedding is determined based on a multi-objective optimization to improve the system VSM and minimizing the cost incurred in the case of predetermined events. The use of Integral Square Voltage Magnitude (ISVM) indicator computed by PMU data is suggested by [14] to improve the SPS decision system.

Frequency stability of power system in the case of contingencies is the target of SPS design which is addressed in some Refs. [15–17]. In [15], an adaptive load shedding method is presented that the proper amounts of shed loads are determined according to system frequency and voltage falling rate to preserve the frequency and voltage stability of power system. In [16], a learning machine-based prediction method is used to determine event-driven load shedding in real-time conditions to prevent frequency instability in the fault occurrence conditions. [17] presents an experience of design, implementation and operation of the SPS for Kinmen power system in Taiwan that compensates the drawbacks of the existing UFLS protection scheme to prevent system blackout.

The authors of [18–34] present the SPS design regarding the transient stability of power system. In [18], a method for determination of proper capacity of static synchronous compensator (STATCOM) is presented to improve the system transient stability and reduce the number of tripping generators in SPS operation. [19] proposes a new online SPS method that, in comparison to the traditional SPS designed annually and based on offline simulations, is more secure and increases the economic benefits of remedial actions. In [20], a PMU based SPS is proposed that estimates the power system transient instability by equal-area criterion of One Machine Infinite Bus (OMIB) equivalent system. [21,22] also use the PMU online data to enhance the reliability of SPS arming and [23] proposes a risk-assessment method to determine the optimal parameters for better performance of an online SPS. In [24,25], the effects of communication system delays on the adequate operation of the SPS in transient stability are investigated. In [26], a method of increasing the robustness of communication-based SPS is presented by using an Exponential Weighted Moving Average (EWMA) scheme. From the reliability viewpoint of SPS, the Markov modeling method and Dynamic Security Assessment (DSA) tool are proposed in [27] and [28], respectively, to analyze the SPS reliability. In some references, the application of fast valving and breaking resistor for transient stability improvement are studied [29–34].

Some economic derivers of SPS implementation such as increasing the power transfer capability and the possibility of high renewable resources penetration are presented in [35–45]. In [35,36], the economic drivers of SPS implementing in Chilean electricity market are addressed. One of the most important proposed motivations is the capability of SPS to guarantee the system stability in the high penetration levels of solar energy. [37] surveys the economic and technical drivers of SPS implementation in Iranian power system specially the possibility of wind farms integration into a congested grid. The authors of [38] propose the SPS design according to an Artificial Neural Network (ANN) to preserve the system transient stability in an offshore island with high penetration of solar energy. In [39], a load shedding SPS is proposed considering the wind farms dynamics and the turbine-generator detailed model to improve the system voltage stability. [40] presents the use of SPS to mitigate the congestion in the Western United States power system. In [41], also the experiences of technical and economic benefits of SPS in the Hydro Quebec power system are explained. Ref. [42] illustrates the application of SPS in the Southwest Region of the United States to increase the transfer capability. In [43], the SPS reliability assessment is formulated as a risk-based cost optimization problem. The analysis of this paper shows that the cost saving of SPS utilization, by increasing transfer capability and relaxation of security constraints, is more considerable in comparison to the cost of SPS operation failures. [44] suggests a framework for risk and benefit assessment of SPS application for network congestion management. In [45], a procedure of secure and dependable design of SPS for increasing transfer capability is proposed that uses fault tree analysis and minimal cut sets theory to assess the SPS reliability. The economic motivations and technical design criteria of SPS mentioned in above references are summarized in Table 1.

In addition to the aforementioned works, presentation of a mechanism for economic design of SPS considering the electricity market environment is a new subject that is proposed in some Refs. [46,47]. An optimal UFLS method in a restructured environment is proposed in [46] that includes two steps. In the case of event that causes the system active power unbalance, initially, the total amount of load shedding requirement is calculated to keep the frequency in an allowable range. Thereafter, the exact location and amount of load shedding are determined by maximizing the social welfare. Due to the need for fast actions following a contingency, time consuming calculation in real time can be a disadvantage of the proposed method. In [47], the economic aspect of SPS design in a single-area power system with a centralized electricity market is studied in which the amount and location of remedial actions are determined offline, by maximizing the social welfare as well as minimizing the loads outage costs, while the static security constraints are considered. For each specified contingency, the selected remedial actions are prepared based on a lookup table to be done in real time conditions.

In the above references, economic-based design of SPS has been investigated in the single area power system with a centralized market environment. However, regarding to the increasing interest in energy exchanges among the electricity markets in multi-area power systems, in some papers the Multiple Electricity Markets (MEM) are addressed as the market coupling [48–53]. In these interconnected power systems,