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Optimal generation units start-up sequence during restoration of power system considering network reliability using bi-level optimization

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ABSTRACT

During recent years power systems are operated near the nominal capacity of system equipment with low stability margin. Operation of power systems in this condition is extremely risky and power systems lose their stability with any intense failure of system equipment. In bulk power system, it is more critical and may cause a partial or overall blackout. The capability of black start to bring back system to a normal condition in the case of partial or overall shut down is very important in each power system. When a shutdown occurs, power plants with black start capability supply cranking power for non-black start power plants, pick up critical loads and energize required transmission lines. These actions should be done in minimum time interval to maximize system provided energy during the restoration process. Most important decision making during restoration process is the determination of start-up sequence of generation units. During the restoration process, units with black start capability (BS units) start at the beginning of the process to provide cranking power for non-black start units (NBS units). Hence the determination of NBS units is decision variable in the restoration problem. In this paper, this problem has been described as a bi-level optimization problem which in upper level determines the optimal start-up sequence of NBS units by using a Teaching-Learning Based Optimization algorithm and in lower level determines the optimal transmission path with minimum number of switching and maximum reliability between any two necessary buses using the searching path graph-based algorithm. The proposed approach has been implemented successfully on IEEE 24-bus RTS and IEEE 118-bus test systems.

1. Introduction

Blackout of the power system is an infrequent phenomenon in power systems, but when it happens, it will have many effects on economics, industries, and society. Restoration of power system had been always one of the serious operating problems from the advent of power systems. In the recent years, increasing the electricity demand and changing the structure of industries cause to operate power systems near full capacity with small stability margin. On this operating condition, each intense fault in the power system can destroy the system normal condition and maybe cause to partial or overall blackout [1].

Whenever power interruption happens, it is essential to return the system to its normal state or to an optimal operating condition as soon as possible. As it is shown in Fig. 1 in most of the time power system is in normal condition, when a fault occurs, the system goes to alert state in which it can go back to normal state by applying preventive control, if more fault occurs system go to emergency state and emergency control need to be applied to bring back system to alert state, otherwise cascading faults result in going system to the extreme state in which some parts or overhaul of the system is out of service. At this state, power system should be brought back by resynchronization, restarting and load pick up action to transmit to normal or alert state [2].

The process of bringing back the network to a target network is called power system restoration. This process is a multi-objective, multivariable, multi-constraint and mixed integer optimization problem and very difficult to solve. As shown in Fig. 2 the restoration planning is divided into three stages: restarting generating units, establishing transmission network and load restoration [3].

The restoration of the power system is started from the black-start (BS) units. With the transmission of BS generated power through transmission lines, the initial power required to start up nonblack-start (NBS) units is provided. At the same time as starting up units and by increasing the power generation capacity in the system, the loads will be connected to the system to maintain the stability of the power system [4].

Generating units are divided into two groups based on the required

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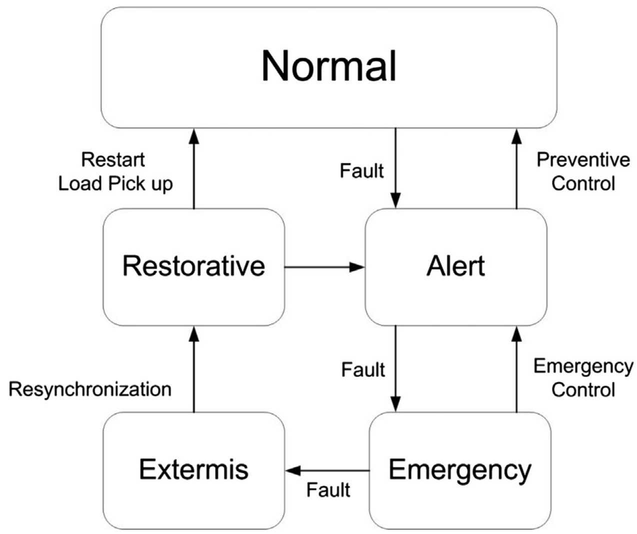

Fig. 1. Operation states of the power system.

power to start up: BS units that can start with their internal resources without using external power sources, and NBS units that are required to external power resources for starting up [5].

BS units include three groups of units:

Hydro units: These units require very little initial start-up energy to open the water intake valve. They have high response speeds and can provide the power needed to start up large fossil units and atomic units.

Diesel units: Diesel generators are usually started quickly by the battery resources. These units provide the power needed to start up larger units. The size of these units is small and is generally not used to energize the large transmission equipment.

Gas turbine units: Aerodynamic gas turbines can be started with the help of battery resources. Larger gas units are equipped with diesel generators, which energize the auxiliary unit and start the gas turbine. The speed of starting the gas turbines is high and can provide the required power for a portion of the system loads in a short time.

Depending on the structure and characteristics of the power system, the process of restoring each system is different from one another. In power systems with a high number of BS units, due to the availability of sufficient initial power resources, the power system is restored quickly, while in power systems with a limited number of BS units, the system restoration is more complicated and more time-consuming. In this paper, the restoration of ordinary power systems with a limited number of BS resources is discussed.

Because of the importance of restoring power systems, many researchers have worked on the power system restoration issues. In [6], an overview of the most important failures that led to blackouts in the North American Electric Reliability Council (NERC) during the period 1979 to 1983 has been reviewed. In this review, the problems encountered with system restoration in this 5-year period have been discussed. In [7] Various issues related to the process of restoring power systems have been studied. These issues are included:

- The characteristics of the steam and gas turbines
- The role of the control system in restoring the power system with electrical, mechanical and frequency considerations
- Controlling and maintaining the reactive power balance of the system
- The dynamics and stability of the power system during the restoration
- Intentional islanding

Switching strategy, protection system during restoration, restoration training, standing phase angles and load pickup have been discussed in [8,9]. Many researchers focus on the units' start-up sequence which is the most important feature of restoration problem. In [10] a new formulation for start-up sequence of generation units as a MILP problem is presented. The optimization problem is so modeled that maximize the overall generation capability of power system in the first hours after system outage. A VIKOR based method is proposed in [11] for determining the start-up sequence of units considering different and changing requirement during the restoration of power system. In [12] an offline restoration planning for power system is formulates by supporting wind energy to minimize the restoration time. Various factors, including location of wind generator, uncertainty, fluctuation, penetration, and inertia control capability are explored. application of pumped-storage Hydro beside wind energy on restoration of power system in order to compensate the uncertainty of wind energy are demonstrated in [13]. A new start-up timing characteristic for the generating units which best determined the behavior of the units during the restoration process has been introduced in [14]. In this article, a backtracking method is implemented to find optimal start-up sequence of generators. In addition, an A-star search algorithm that is a heuristic algorithm has been used to identify the shortest path between nodes in the power system. An ant colony search method is applied to a 39-bus test system to find the optimum generator start-up during power system restoration [15]. A combined algorithm using CPLEX have been proposed in [16] to determine the NBS units start-up sequence. In this article, for three different location of BS unit, start-up sequence has been calculated to determine the effectiveness of the location of BS unit on the restoration process. Numerical result shows that changing the location of BS unit leads to a different restoration process. Effects of renewable energy resource include wind power and solar power on power system restoration have been considered in [17,18]. In These articles, it is considered that renewable energy will be employ after last NBS unit has been started. Taking part renewable energy resource in power system restoration leads to decrease system unnerved load during restoration process.

In bulk power systems, it is more satisfying to sectionalize power system into some islands for parallel restoring of the power system. Parallel restoration consists of several steps: First step is dividing the system into some islands. The second step is restarting units and energizing each island. The third step is serving loads in each island to maintain stability and restore them and forth is reconnecting islands to each other's via tie lines and make the integrated power system. Parallel restoration decrease the time of returning the network significantly and increase the success of the restoration process [19].

One of the difficulties of power system restoration is to find optimal path for transmitting cranking power form BS units to NBS units and from energized buses to unenergized buses. In [20] a method of using Phasor Measurement Units (PMUs) is proposed to identify the optimal path during the restoration of the power system. A connectivity matrix [A] is used to find the transmission path with minimum number of lines. Bellman-Ford Algorithm has been used in [21] to identify the optimal path in power system during restoration. In this paper path with minimum losses has been considered as the shortest transmission path. In [22] optimal path search problem has been formulated as MILP problem by defining a set of logical constraint for energizing the transmission network.

In most of the existing research works, optimal start-up sequence determination and optimal path selection have been executed separately [23] because of complexity and time-consuming of the restoration process. Consequently, network constraints may be violated and result in an infeasible solution. Also reliability of network equipment especially transmission lines have not been considered in power system restoration studies. In this paper, a new bi-level optimization algorithm has been introduced to determine simultaneously the optimal units' start-up sequence and optimal transmission path during the restoration process. Reliability of transmission lines has been considered when selecting optimal transmission path in order to increases the success