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Sectionalizing strategies for minimizing outage durations of critical loads in parallel power system restoration with bi-level programming

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A B S T R A C T

Fast restoration of critical loads and non-black-start generators can significantly reduce the economic losses caused by power system blackouts. In a parallel power system restoration scenario, the sectionalization of restoration subsystems plays a very important role in determining the pickup of critical loads before synchronization. Most existing research mainly focuses on the startup of non-black-start generators. The restoration of critical loads, especially the loads with cold load characteristics, has not yet been addressed in optimizing the subsystem divisions. As a result, sectionalized restoration subsystems cannot achieve the best coordination between the pickup of loads and the ramping of generators. In order to generate sectionalizing strategies considering the pickup of critical loads in parallel power system restoration scenarios, an optimization model considering power system constraints, the characteristics of the cold load pickup and the features of generator startup is proposed in this paper. A bi-level programming approach is employed to solve the proposed sectionalizing model. In the upper level the optimal sectionalizing problem for the restoration subsystems is addressed, while in the lower level the objective is to minimize the outage durations of critical loads. The proposed sectionalizing model has been validated by the New-England 39-bus system and the IEEE 118-bus system. Further comparisons with some existing methods are carried out as well.

Introduction

Despite the fact that modern power systems operate in feasible and reliable environments under the supervision of advanced protection devices and control technologies, it is still possible that they are exposed to cascading failures and large-area power outages. Several major blackouts have taken place in the past few years, such as the massive blackout in North America on August 14, 2003 [1] and a major disturbance in India in July, 2012 [2]. In order to minimize the economic losses caused by blackouts, the establishment of effective and rapid power system restoration strategies is becoming a very important issue [3]. Power system restoration has always been a complex and diverse problem due to the various dynamic characteristics, operating constraints and restoration objectives [4]. As a result, the entire power system restoration process is commonly divided into different stages, including startup of black-start (BS) generators, network reconfiguration, the resynchronization of islanded subsystems and the restoration of power loads. Considerable research has been done on various stages of power system restoration [4–9].

The process of power system restoration always takes quite a long time because of a lack of operational data and the complexity of system restoration itself [10]. Generally, in the early stage of restoration, the blackout area is divided into several restoration subsystems to accelerate the restoration speed before they can be synchronized. As a result, the power system restoration procedure will be significantly affected by the divisions of restoration subsystems and the restoration sequence of non-black-start (NBS) generators as well as critical loads. If the characteristics of cold load pick-up (CLPU) are to be considered, the coordination between load restoration and generators' loading will become a more important issue for maintaining the power balance of the newly restored system. However, most existing sectionalizing methods aim to build an optimized skeleton network or minimize the outage times of NBS generators, while the coordination of

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generator loading and critical load pickup have not been paid enough attention.

Generally, sectionalizing strategies are used in two aspects in power systems: preventing cascading failures and dividing restoration subsystems after a blackout. Whenever the system operators detect a potential cascading event, sectionalizing strategies will be activated to separate the bulk system into controlled islands so as to prevent a global blackout [11–13]. In case that a blackout occurs, sectionalizing strategies can also help the operators to accelerate the restoration procedure. In fact, the power loads after a blackout are unlikely to vary continuously due to the operating of switches, characteristics of cold loads, lack of automatic control devices and unpredictable behaviors of electricity customers [14]. Thus, the pick-up characteristics of loads and the balance between generation and demand are the most important factors having impacts on the restoration process and the loading of generators. This paper focuses on the sectionalizing strategies during the initial stage of power system restoration after a global power failure, with a special emphasis on the coordination of generator ramping and the pickup of critical loads, so as to ensure that generating units and outage loads be restored as fast as possible. The sectionalizing model consists of integer variables and non-linear constraints, and a bi-level programming approach could be used to solve the developed model.

The remainder of this paper is organized as follows. Section "Formulations of sectionalizing strategies" formulates the optimization model with the characteristics of CLPU and NBS start-up considered. In Section "Solving the sectionalizing model", a bi-level programming approach and the formulation of initial subsystem divisions are presented. Section "Simulation results" presents the simulation results of the New England 39-bus system and IEEE 118-bus system, and comparisons with some existing methods carried out. Conclusions are presented in Section "Conclusion".

Formulations of sectionalizing strategies

Characteristics of CLPU and generator loading

When BS generators resume working after a global blackout, most automatic control devices are under manual control, the coordination of power load and generator loading is closely related to startup characteristics of power loads, NBS generating units and the frequency response of prime movers [10].

Characteristic of load pickup

An appropriate amount of load pickup during restoration helps keep the active and reactive power balance of power system and coordinated with the loading of generators. In actual power systems, most loads are supplied by a distribution system concerned, instead of a high-voltage transmission system. Thus, the available load capacity directly connected with the transmission system may not be sufficient to support the rated ramping of generating units. As a result, once a bus in the transmission system is restored, the local distribution system operator should carry out switching operations to integrate critical loads into the newly restored transmission system following the control signal issued by the transmission system operator [14].

Typically, the pickup of the power loads results in a peak demand inrush of both active and reactive power. This characteristic known as CLPU is applicable to loads such as air conditioners, electrical heating and refrigerating devices. The characteristic of CLPU must be considered strictly in making restoration plans. Otherwise, a sudden inrush of excessive load current could result in some issues such as voltage sags and frequency drops, and hence may threaten the still fragile newly restored power system. In this work, all critical loads in the blackout area are assumed to have cold load features.

The behavior of CLPU is a complex process concerned with environmental temperature, outage duration and mechanism of cold load devices [15], etc. A simplified power consumption characteristic for CLPU is demonstrated in Eq. (1) [16]. Assume a cold load with rating active power of $P_{CL,N}$ is reintegrated into the restored subsystem at time T_{S0}, and the practical active power consumption of this load is denoted as $P_{CL,t}$ at time t. During the period from T_{S0} to T_{S1}, a peak power consumption estimated as $K_cP_{,N}$ is caused by the effect of CLPU and K_c denotes the overload coefficient of CLPU. The overload effect of CLPU decays after T_{S1} and gradually ends by time T_{S2}. However, a certain amount of loads could not be integrated right at time T_{S0} due to the delay of both breaker operations and the response of electricity consumers. Thus, after the overload effect of CLPU finishes, it still takes some time when the power consumption stabilizes at its nominal value $P_{CL,N}$. As shown in Eq. (1), the load demand slightly increases from $K_sP_{,N}$ to the nominal load $P_{CL,N}$ during the period T_{S2} to T_{S3}, and K_s denotes the delay coefficient of load pickup.

$$P_{CL,t} = \begin{cases} 0 & t < T_{S0} \\ K_cP_{CL,N} & T_{S0} \leqslant t < T_{S1} \\ \frac{K_c(T_{S2}-t)+K_s(t-T_{S1})}{T_{S2}-T_{S1}}P_{CL,N} & T_{S1} \leqslant t < T_{S2} \\ \frac{K_s(T_{S3}-t)+(t-T_{S2})}{T_{S3}-T_{S2}}P_{CL,N} & T_{S2} \leqslant t < T_{S3} \\ P_{CL,N} & t \geqslant T_{S3} \end{cases} \quad (1)$$

Meanwhile, the reactive power consumption characteristic of CLPU cannot be ignored as it affects the system's reactive power balance and voltage profiles. In this paper, the reactive power consumption characteristic of CLPU is assumed to be the same as that of active power. The rating reactive power of the cold loads is denoted as $Q_{CL,N}$, then the reactive power consumption at time t which is denoted as $Q_{CL,t}$ can also be obtained through overload coefficient and the delay coefficient are represented by K_{qc} and K_{qs}, respectively.

Startup features of NBS generators

Generating units with BS capabilities will restart first after a blackout. However, NBS generators cannot resume normal operations without startup energies. Moreover, it still takes a certain period of time until the NBS generators are able to output power after they are energized. Generally, the duration of generator startup process varies with the type of generators [17]. In this paper, all the NBS generators are assumed to be thermal generators, and the simplified startup feature of thermal generating units is illustrated in Eq. (2) [4].

$$P^{\max}_{G,t} = \begin{cases} 0 & t < T_{G0} \\ -P_{start} & T_{G0} \leqslant t < T_{G1} \\ -P_{start} + R_G(t - T_{G1}) & T_{G1} \leqslant t < T_{G2} \\ P_{\max} & t \geqslant T_{G2} \end{cases} \quad (2)$$

Assume an NBS generating unit is cranked at time T_{G0}, and the maximum active power output of the NBS generating unit at time t is denoted as $P^{\max}_{G,t}$. From T_{G0} to T_{G1}, auxiliary equipment is restored and the preparations to start the blackout turbine are made. After the turbine start up at T_{G1}, the restored generator picks up the auxiliary loads step by step and is finally able to output power by continuous ramping with the ramping ratio of R_G. Ideally, the generator will keep ramping continuously until the maximum generation output is reached at T_{G2}. P_{start} and P_{max} denote the start-up power demand and the maximum generation output of the NBS generating unit, respectively.