Electrical Power and Energy Systems 90 (2017) 147–157

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Coordinating self-healing control of bulk power transmission system based on a hierarchical top-down strategy

Xi Cao [a], Hongtao Wang [a,*], Yutian Liu [a], Rasoul Azizipanah-Abarghooee [b], Vladimir Terzija [b]

[a] Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education, Shandong University, Jinan, China
[b] School of Electrical and Electronic Engineering, University of Manchester, Manchester, UK

ARTICLE INFO

Article history:
Received 2 November 2016
Received in revised form 5 January 2017
Accepted 6 February 2017

Keywords:
Bi-level optimization
Decision support system
Coordination mechanism
Power system restoration

ABSTRACT

Top-down power system restoration following a widespread blackout begins with energization of the backbone transmission network. All interconnected regions will be restored as a whole, which needs collaboration of multiple operators. The parallel control and integrated restoration planning issues have to be addressed. In order to conduct an efficient top-down restoration process and guarantee the operational security, a hierarchical coordination mechanism and an online decision support system-based self-healing approach are proposed. Considering the multiple decision-making problems involved, an associated bi-level optimization model is built, which integrates the planning problems of backbone reconfiguration, sub-transmission system restoration, and non-black-start units start-up. Then, a solution methodology is developed to provide online decisions based on the model. Simulation results of Shandong Power System in China show that the restoration performance is significantly improved using the proposed control approach. Additionally, the decision method is proved to be efficient enough for online applications.

1. Introduction

Although modern power systems are highly reliable, catastrophic widespread blackouts still can't be avoided [1,2]. When a blackout occurs, the utilities have a responsibility to restore the power system as expeditiously as possible. During a typical restoration procedure, transmission system restoration (TSR) is a critical stage prior to large-scale load pick-up [3,4]. In a TSR process, long-distance transmission lines will be energized to rebuild the bulk power network and deliver cranking power from black-start resources (BSRs) to major non-black-start (NBS) plants out of service. The major concerns of a TSR problem are voltage security and system stability, the reconfiguration strategy of transmission network, and the start-up sequence of NBS units.

Generally, two types of restoration strategies can be deployed in the TSR procedure, (i) the *bottom-up* strategy and (ii) the *top-down* strategy [3,5]. When internal BSRs are sufficient, *bottom-up restoration* would be more efficient. By dividing the blackout area into several subsystems, multiple independent restoration procedures can take place simultaneously. Therefore, the total restoration process is speeded up. The technical problems along a *bottom-up restoration* process are discussed in [6]. Different sectionalizing methods are proposed in [7–10]. The advantage of *bottom-up restoration* is to decompose a complex problem into several simpler ones [8]. The modeling and solving process are easier. The TSR procedure will be executed in a decentralized way. So frequent interactions between operators can be avoided.

However, when internal BSRs are insufficient, the advantage of *bottom-up restoration* would not be reflected. In such circumstances, *top-down restoration* will be a better option, especially when the external power support is available and a strong backbone system exists. Some utilities also choose the *top-down* approach as the primary strategy as they have some internal BSRs directly interconnected to the extra high voltage (EHV) network [11]. The advantage of *top-down restoration* is the rapid deployment of MW resources by initially energizing the EHV circuits. With considerable EHV transmission corridors, it is relatively easy to restore the local sub-transmission systems and provide the auxiliary power to the NBS plants that distributed in the wide area [5].

Unlike the *bottom-up* strategy, *top-down* restoration is more complex. All the operations distributed in different regions and executed by different operators are handled as a whole. The

Abbreviations: TSR, transmission system restoration; NBS, non-black-start; BSRs, blackstart resources; EHV, extra high voltage; LFP, local feeding point; DSS, decision support system; DTS, dispatcher training system.

* Corresponding author.
E-mail address: whtwhm@sdu.edu.cn (H. Wang).

http://dx.doi.org/10.1016/j.ijepes.2017.02.004
0142-0615/

Nomenclature

n_L	number of LFPs
$n_{C,i}$	number of EHV transmission lines that are energized prior to the restoration of LFP i
$n_{LC,ij}$	number of transmission lines within the local restoration path of plant j
$n_{P,i}$	number of NBS plants in the local system where LFP i is located
$n_{G,ij}$	number of NBS units in plant j
$n_{Gstable}$	total number of NBS units that reach the minimum stable output
n_{Gtotal}	total number of NBS units in the system
n_B	number of nodes that needs to be restored within the local cranking paths
n_{ES}	number of substations along the EHV transmission corridor
$P_{total,i}$	total MW consumption in the local system where LFP i is located
$V_{i,\max}$, $V_{i,\min}$	upper and lower limits of the steady state voltage of node i
V_i	EHV bus voltage of LFP i
$T_{E,\ j}$	switching operation time for energizing line j
$T_{C,\ j}$	switching operation time of compensation equipment before energizing line j
t_0	beginning time of restoration
T	ending time of a defined restoration period
$P_k(t)$	generation output function of NBS unit k
$P_{Gstart,i}$	start-up power requirement of plant i
P_S	current allocable MW resource of the system
$P_{Sinitial}$	initial MW resource of the system
$P_{G\max,j}$	capacity of unit j
$P_{G\min,j}$	minimum stable output of unit j
k_i	indication whether unit i has got the power quota at previous stages (1 for true, 0 for false)
Ω_{LFP}	set of target LFPs
t_{start}	unit start-up time
T_{start}	duration of the unit start-up process
r	ramping rate of unit
$T_{s,h}$, $T_{s,c}$	hot-start and cold-start time of unit
T_{CH}, T_{CC}	maximum hot-start and minimum cold-start critical time of unit

restoration can be vulnerable to uncertainties and delays. Decentralized control is not suitable anymore since all the involved regions are directly interconnected. A hierarchical organizational structure is essential. Normally, a central coordinator, e.g. Reliability Coordinator in North America or higher-level Dispatch Center in China, is designated to lead the whole restoration procedure. The key challenges of conducting a *top-down* TSR include: (i) centralized restoration planning from a global perspective, and (ii) efficient coordination control among multiple parallel restoration processes.

Multiple decision-making problems will be involved in the planning process. First, the restoration paths and the NBS units start-up sequence should be carefully determined. These two problems have been widely discussed in previous studies. In [12–14], the concepts of power transfer distribution factor and electrical betweenness are used respectively to determine the restoration path. The node importance assessment-based network reconfiguration strategies are proposed in [15,16]. In [17,18], different models are presented to solve the start-up sequence problem of NBS units. However, since the *top-down* TSR is organized in a hierarchical manner, these methods cannot be directly utilized. Generally, a coarse-grained optimization is required at the central level to determine an energization direction. Then, the restoration paths and sequence will be arranged based on this guideline. Another critical concern during this process is reactive power balance and overvoltage control. Specific compensation and voltage regulation measures should be determined before energizing the EHV transmission circuits. These issues have been discussed in [19,20]. Since voltage control is essential and time consuming in *top-down* TSR, it should be integrated into the determination of restoration paths.

A *top-down* TSR may cover several independent control areas and require collaboration of multiple utilities. The coordination issues should be carefully considered. As the initial supply of cranking power is limited and all will be allocated through the EHV network, it is important to properly organize the restoration actions that distributed in different regions. In [21], a tie line-based collaboration strategy is presented to share BSRs among neighboring systems. Such collaboration is still based on a *bottom-up strategy*. Considering the tight coupling of operations in a *top-down* TSR, specific mechanism for coordination control should be developed. On the other hand, as the spatial and temporal span of *top-down* TSR is large, reasonable and timely response to various contingencies is also essential. Traditional 'manual' restoration based on offline decision tools cannot manage the uncertainties well. Development of online decision support system (DSS) provides a solution for this problem [22,23]. In order to achieve a robust control process, a specific response mechanism for triggering such a DSS is required. It is also important to guarantee the flexibility and efficiency of such DSS.

Taking into account the above concerns, a coordinating self-healing control method of *top-down* TSR is proposed in this paper. First, the general implementation strategy and the involved multiple restoration tasks are analyzed. Then, a novel hierarchical coordination mechanism among the operators is established. By introducing a local feeding point (LFP) concept and setting up associated indexes, specific strategies of cranking power allocation, overvoltage prevention, information sharing and contingency handling are provided. Under this mechanism, a DSS-based self-healing approach is proposed to facilitate the decision-making and execution of *top-down* TSR. In order to provide comprehensive and optimal decisions from the whole system perspective, restoration planning of *top-down* TSR is modelled as a *bi-level* optimization problem and an efficient solution methodology is proposed. A case study of Shandong Power System in China is presented to verify the efficacy of the method.

The paper is organized as follows. Section 2 introduces the control framework of *top-down* TSR. Section 3 describes the bi-level optimization model. In Section 4, the associated algorithms are introduced. The case study results are presented and discussed in Section 5, followed by conclusions.

2. Control framework of top-down TSR

In this section, a general implementation strategy of *top-down* TSR is described and a corresponding hierarchical coordination mechanism is proposed. The associated decision-making problems are analyzed and an online DSS-based restoration planning and self-healing control framework is presented.