Electrical Power and Energy Systems 53 (2013) 664–674

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

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

A new method for standing phase angle reduction in system restoration by incorporating load pickup as a control means

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ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form 8 May 2013
Accepted 21 May 2013

Keywords:
Power system restoration
Load restoration
Standing phase angle
Transmission loop closure
Load pickup
Generation rescheduling

ABSTRACT

In restoring a power system after a major disturbance, system operators often encounter an excessive standing phase angle difference (SPA) between two buses of a circuit breaker when a transmission line is energized and results in a loop closure. Under such a condition, there is high risk of damage to nearby generators and other equipments for the breaker/loop closure operation. Since the SPA value is a function of the restoring system topology, load and generation injections, the SPA reduction becomes an important problem in system restoration. Presently, generation rescheduling is adopted as a primary control means and load shedding is used as the final resort to reduce the SPA. In fact, there remains a lot of unserved load in the system throughout the restoration process. Since the unserved load that can help reduce the SPA is not picked up and selected as a control means, the existing control strategy for SPA reduction is not optimal for a system under restorative state. In this paper, a new method that incorporates load pickup as a control means is proposed to address the SPA reduction problem. Firstly, a general principle for SPA reduction is established, i.e., a smaller SPA can be achieved by lowering the total active power flow transmitted from the sending-end to the receiving-end subsystem. Based on which, the pickup of load in the sending-end subsystem and the increased active power generation in the receiving-end subsystem are combined as control means. Then a mixed integer nonlinear programming (MINLP) algorithm and an alternative two-stage decoupled (TSD) algorithm are proposed to develop specific control strategies. The algorithms can help restore some unserved load during the process of SPA reduction and, thus, are more effective in achieving the goal of power system restoration. Simulation results on the New England test system demonstrate the effectiveness of the proposed algorithms.

1. Introduction

A large disturbance can cause a power system to experience a partial outage or even a complete blackout. If an outage or blackout occurs, restoration operations should be performed as quickly as possible to minimize the downtime and costs to consumers. The restoration process includes three time periods or stages, i.e., preparation, system restoration and load restoration [1]. During the last two periods, transmission lines are selectively energized to recreate a skeleton transmission network and to firm up the network [2], respectively. In the third restoration period, the newly energized transmission lines are particularly more likely to result in transmission loops. If a transmission loops is to be formed, it is important to ensure that the excessive voltage standing phase angle difference (SPA) between two buses of the circuit breaker is within an allowable limit [3].

Compared with the voltage magnitude difference, the adjustment and control of an excessive SPA is more complex, as the SPA value is a function of the restoring system topology, load and generation injections. To address this issue, a SPA reduction program is usually called to assist system operators in efficiently performing the transmission loop closure operation during the restoration process [4]. In [5], the concept of "generic restoration milestones (GRMs)" is proposed by generalizing various restoration actions in different restoration stages. Utilizing the concept, a software entitled "System Restoration Navigator (SRN)" has been developed [6]. The specific restoration strategies can be constructed by a combination of GRMs in the context of actual system characteristics and conditions. It can be found that the SPA reduction program is an important tool in GRM2 for establishing available transmission paths. To realize the program, several models have been proposed. Methods such as sensitivity-based heuristic analysis, mathematical programming, and artificial intelligence have been used to develop specific control strategies. Within these methods, active power generation rescheduling is adopted as a primary control means, and load shedding is used as the final resort. In [7,8], sensitivity-based SPA reduction methods are proposed, where a SPA between two specific buses is expressed as a linear combination of the change in real power injections. This method can act as a direct aid to reduce the SPA. However, security

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http://dx.doi.org/10.1016/j.ijepes.2013.05.039

Nomenclature

i	bus counter
s, t	circuit breaker counters at bus i
U_s, P_s, Q_s	voltage magnitude, active and active power of the sending-end bus
U_r, P_r, Q_r	voltage magnitude, active and active power of the receiving-end bus
R, X, Z	resistance, reactance and impedance of a transmission line
P_{gi}, Q_{gi}	active and reactive power outputs of the generator at bus i, respectively
P_{gi0}	initial active power output of the generator at bus i
$P_{gi}^{\max}$	upper limit of the active power output of the generator at bus i
$Q_{gi}^{\max}$, $Q_{gi}^{\min}$	upper and lower limits of the reactive power outputs of the generator at bus i, respectively
ΔP_{gi}	active power deviation of the generator at bus i, $\Delta P_{gi} = P_{gi} - P_{gi0}$
ΔP_{dis}, ΔQ_{dis}	unserved active and reactive load on the sth feeder at bus i
$\Delta P_d^{\max}$	maximum amount of load that can be safely picked up
x_{is}	status of the circuit breaker of the sth feeder at bus i. If the circuit breaker is selected to be energized, then x_{is} is set to 1, otherwise $x_{is} = 0$
w_{is}	Percent of important load on the sth feeder at bus i
U_i, θ_i	voltage amplitude and phase angle of bus i, respectively
$U_i^{\max}$, $U_i^{\min}$	upper and lower limits of the voltage amplitude of bus i
θ_{ij}	standing phase angle difference (SPA) between bus i and j, $\theta_{ij} = \theta_i - \theta_j$
θ_{set}	maximum allowable limit for SPA
P_{di}, Q_{di}	active and reactive load at bus i, respectively
G_{ij}, B_{ij}	conductance and susceptance of branch $i - j$, respectively
S_{ij}, $S_{ij}^{\max}$	complex power flow across branch $i - j$ and is its upper limit
$\Delta f_{\max}$	maximum allowable drop of the system transient frequency
s_{li}, s_{gi}	sensitivities to the reduction of SPA with respect to the load pickup and the active power generation increment at bus i, respectively
α	weighting factor for the active power generation deviation
obj	value of objective function
S_B, S_G, S_L	set of system buses, generator buses and branches
S_{pl}	set of feeders in the sending-end subsystem and to be energized

constraints on the system affected by generation rescheduling and load shedding are not considered. In [9], a method that based on linearization and quadratic programming is proposed for SPA reduction, in which the branch power flow, active power generation, and SPA constraints are taken into account. In [10], a two-step method for SPA reduction is proposed. The binding constraints are firstly identified to relieve the computational burden of the following linearization-based generation rescheduling optimization. In [11], a nonlinear optimal power flow (OPF) model is proposed to formulate the SPA reduction problem. In [12], the impact on the rotor shaft torque (RSI) due to the transmission loop closure operation is also included in the OPF model and the Bender's decomposition technique is adopted to solve the problem. In [13], the trajectory of reducing the SPA is traced by the continuation method. In the continuation process, the sensitivity technique is used to identify the most efficient generators in reducing the SPA. Then the amount of active power generation rescheduling is obtained by solving augmented power flow equations. The small signal stability analysis and time domain simulation are performed after the rescheduling to verify the stability of the system. In contrast to the methods in [9–12], the optimization is avoided at the price of a suboptimal solution and high computational burden. In [14], both the active generation rescheduling and load shedding are adopted as control variables for SPA reduction. Considering that the load shedding is completed through switching operations, the SPA reduction is formulated to be a mixed integer nonlinear programming (MINLP) problem. A modified genetic algorithm is utilized to obtain optimal strategies.

Although these methods can guide system operators in quickly accomplishing the transmission loop closure operation without trial and error, they are still not sufficient to address the SPA reduction problem during the restoration process for a few reasons. On one hand, there remain a lot of unserved load in the system throughout the restoration process. Some unserved load can be picked up and selected as a control means to help reduce the SPA. In this case, both the objectives of load restoration and SPA reduction can be simultaneously achieved. However, in the existing methods for SPA reduction, no load is picked up and active power generation reduction is needed. From the point of minimizing the unserved energy/maximizing the total restored load, they are suboptimal for a system under the restorative state. On the other hand, general principles underlying these methods have not been intensively analyzed and guidelines for SPA reduction have not been provided. When the SPA reduction program is not usable or available, the general principles and guidelines for SPA reduction will provide significant assistance for system operators to flexibly deal with unseen restoration scenarios [15,16]. Thus, to some extent, it is believed that these principles and guidelines are also of significant importance as specific control strategies.

To improve the above methods for dealing with the SPA reduction problem for a system under a restorative state, a general principle is first established. Based on that principle, the load pickup, which has previously been used as a means for frequency and voltage control during the first two restoration periods and used as the main objective during the load restoration period [1], is combined with active power generation increment as control means for SPA reduction. Then, a new MINLP algorithm (in contrast to the MINLP algorithm in [14]) and a two-stage decoupled (TSD) algorithm are proposed to provide specific control strategies. Because nearly the same amount of unserved load can be picked up while increasing the active power generation, SPA reduction and load restoration are realized in a coordinated manner. Thus, the algorithms proposed in this paper are more effective in achieving the goal of power system restoration from the point of maximizing the total restored load, i.e., restoring power demand as soon as possible [17].

This paper is organized as follows. The general principle for SPA reduction is first established and explained in Section 2. The new MINLP algorithm is proposed in Section 3. Section 4 describes the TSD algorithm. Simulation results on the New England 10-machine 39-bus test system are described in Section 5. Comparisons between various methods for SPA reduction are made in Section 6, and Section 7 presents the conclusions of this paper.

2. General principle for SPA reduction

The basic idea for reducing excessive SPA is first explained by using the example of a simple transmission line. Next, the idea is