Electrical Power and Energy Systems 87 (2017) 52–64

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Emergency transmission line switching to suppress power system inter-area oscillation

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ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 22 October 2016
Accepted 26 October 2016

Keywords:
Inter-area oscillation
System brittleness index
Emergency damping control
Transmission line switching
Sensitivity analysis

ABSTRACT

Electromechanical oscillation is an inherent property of ac power systems which can occur in the forms of local and inter-area oscillations. The inter-area oscillations may impose a serious threat on the system if they are not controlled properly. Over the past two decades, many methods have been introduced to control and suppress electromechanical oscillations. This paper proposes a new supplementary emergency damping control (SEDC) to suppress inter-area oscillations. In the proposed approach, a system brittleness index (SBI) is introduced which can show system risk for splitting into uncontrolled islands. Following a sever fault, the value and sign of SBI is used as an indicator for activation of SEDC. By using sensitivity analysis of the inter-area mode with respect to line switching, the most effective transmission line switching (TLS) is utilized as an emergency damping control for suppressing inter-area oscillations. For this purpose, by offline studies, a priority list of the effective lines switching is prepared. Then, in the real time operational environment, by using an optimization algorithm, the most effective line switching is implemented as SEDC activation. The optimization algorithm guarantees system operation against any potential violation due to line switching. The proposed SEDC has been demonstrated on IEEE 39-buses system with promising results.

1. Introduction

Power system islanding which is the main cause for most of system blackouts basically occurs due to unstable inter-area oscillations. Inter-area oscillations typically ranging from 0.1 to 1 Hz have been a serious concern in power systems for many years. These oscillations arise when system machines are categorized into two coherent groups oscillating against each other with low damping [1]. Weak interconnection between two areas including coherent generators, with a large transfer capacity can easily trigger the low frequency inter-area oscillation (LFIO) under some small or large disturbances [2,3] which may force the system to separate into uncontrolled islands with a substantial unbalance of active power, resulting in frequency deviation and eventual collapse of power supply [4]. Damping of inter-area oscillations is one of the major challenges to the electric power system operators. Basically, the damping control methods for inter-area oscillations can be classified into the following two general categories [5].

(1) Device based methods using controlling equipments such as Power System Stabilizers (PSSs) and Flexible AC Transmission Systems (FACTS) devices.
(2) Operation based methods changing system operating conditions such as generation rescheduling (GR), load shedding (LS) and changing network structure.

Power system inter-area oscillations, are intended to be suppressed by the conventional methods such as preventive countermeasures, installing PSS or FACTS stabilizers [6,7] and HVDC controls [8–10]. These devices provide effective long term solutions and have been widely used [11–13]. In this regards, many researches have been devoted to proper design of controllers of PSS, FACTS devices and HVDC. In [14], based on eigenvalue analysis a method for allocating and improving damping ratio of inter-area oscillations is presented. In [10], by using proper PSS and HVDC modulation, a solution for mitigating dominant inter-area mode of South China Interconnected Power System, is presented [15] presented a new method for coordinating PSSs and SVC to damp inter-area oscillations by using Model Predictive Control (MPC) in which the parameters of the PSSs and SVC are determined simultaneously. In [16], by using UPFC and charging (discharging) electrochemical capacitors, a new control methodology is introduced for damping inter-area oscillation in which the sending, receiving

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http://dx.doi.org/10.1016/j.ijepes.2016.10.011
0142-0615/

end voltages of lines are controlled instead of the active and reactive power flows. In [11], a new controlling technique is used for a combination of STATCOM-SMES system for damping of inter-area oscillations in an effective manner.

By using multiple WAMS-based HVDC and FACTS controller a Wide Area Damping Controller (WADC) is presented to provide efficient damping against multiple inter-area oscillation modes under various operating conditions [13]. In [17], by using wide-area signals and $\frac{H_2}{H_\infty}$ robust control for each case, an adaptive damping controller based on the Decision Tree (DT) is designed. In [12], by introducing the delay margin and combining it with conventional design techniques, a systematic approach for considering the effect of communication delays on the design of a WADC for FACTS devices is investigated.

In [18], a fuzzy logic wide-area damping controller (FLWADC) for inter-area oscillations damping is designed and embedded in a static synchronous series compensator (SSSC). In [19], In order to evaluate modal damping coefficient, explicit formulas are derived which is applied to three and four-terminal HVDC transmissions.

In [20], a systematic design procedure of WADC systems by combining PSSs signals selection and Linear Matrix Inequalities (LMI) based robust control design is developed.

In [1], for damping inter-area oscillation, based on WAMs and real time data, an innovative technique is presented in which by using LMIs, an algorithm is developed for control sets of contingencies.

However, such damping controllers may not always provide adequate damping to overcome small signal security issues, for the following reasons [21].

- Requiring long time for manufacturing and installation.
- Possibility of occurring LFIO problem in a short period of time in which conventional damping controllers are not an efficient and economic solution.
- There are some situations for which specific emergency conditions fall beyond what the controllers are designed for.

Therefore, in the case of severe oscillations, these methods may not be sufficient to correctly and quickly avoid catastrophic consequence of whole system collapse [8]. Splitting of Western Electricity Coordination Council (WECC) system into 4 asynchronous islands on August 10, 1996, due to inter-area oscillation (0.224 Hz) following loss of two transmission lines and inability of shunt capacitor banks for controlling voltage, is an example and evidence for inadequacy of conventional controllers such as PSS and FACTs devices for providing proper damping on inter-area oscillation [2,6,22,23]. Such experiences reveal that damping critical inter-area oscillations under the worst operating conditions is a vitally important issue and effective emergency control should be implemented [6]. Also, none-device based methods for improving damping of inter-area oscillations consists part of research activities in this field.

A sensitivity-based GR method for dispatching system generation and maximizing power transfer subject to the small-signal stability constraint under a set of contingencies has been studied in [21]. A novel emergency damping control by using LS and GR as a control strategy is presented in [6] to effectively suppress anticipated inter-area oscillations in system contingency to obtain the optimal locations, amounts and implementing time of emergency control strategy.

In order to improve small-signal stability and voltage stability, a security constrained redispatching procedures is presented in [8]. For enhancing the damping of inter-area oscillations and providing active compensation of delays in the control loop, a new WADC for a selected generator exciter based on Networked Predictive Control (NPC), is introduced in [24]. Power system configuration changing is also utilized as preventive actions to overcome to some operational issues. Since 1980, some studies have been carried out on using TLS for network reconfiguration. Firstly, TLS is used as a preventive tool to solve operational issues. In continue, line overloading problems are solved by corrective TLS [25]. The application of TLS involving alleviation of branch overloading, system voltage and security enhancement is considered in [26]. In [27], by using mixed integer nonlinear programming (MINLP) and robust Benders decomposition algorithm, for improving line congestion, an optimal TLS based on an ACOPF is used which is able to respect voltage security criteria in the TLS problem. Determination of the proper time for applying the emergency damping controller is very essential. In [6], the optimal time for applying EDC is when the magnitude of tie-line power oscillation reaches maximum or minimum. In [28], a DT based predictor is presented for predicting the time of power system islanding in which the total energy absorbed by coherent synchronous generators during unplanned islanding conditions is formulated as an islanding predictor. In [29], an adaptive controlled islanding scheme by using DT as a component of an EDC strategy is proposed from which the time when system tends to uncontrolled islanding can be recognized.

In this paper, for suppressing low frequency inter-area oscillation and preventing power system from uncontrolled splitting, a new approach for emergency transmission line switching (ETLS) based on the sensitivity of damping ratio with respect to line switching is proposed. For this purpose, based on the data provided by WAMS, an on-line brittleness index is evaluated from which the proper time for applying ETLS can be estimated. In on-line decision for finding the most effective ETLS strategy, off-line evaluated sensitivity of damping ratio of inter-area oscillation with respect to all line switching is adopted as a priority list. In Section 2, the overview of the proposed approach is presented. The concept of brittleness of power systems and an index for measuring system brittleness in the emergency condition for activating emergency controller is presented in Section 3. In Section 4, the concept of sensitivity of the inter-area mode with respect to line switching and the procedure for its evaluation is presented. In Section 5, an optimization method for adopting the best ETLS strategy ensuring the minimum load shedding and generation tripping is explained. The proposed approach is demonstrated with promising simulation results in Section 6. Finally, Section 7 concludes the simulation results.

2. Overview of the proposed approach

Fig. 1 shows the structural concept of the proposed approach, denoted as supplementary emergency damping control (SEDC). SEDC consists of different emergency actions including load shedding, generation reduction and line switching which act as the final defense strategy against system uncontrolled islanding leading to blackout. For this purpose, with respect to each potential inter-area oscillatory mode, a priority list of the effective single line switching for suppressing inter-area oscillation is prepared by off-line simulation studies. Then in the real time operational environment, continuously at consecutive time window, by means of WAMPAC, system on-line operating data are gathered and analyzed from which coherent groups of oscillating generators, excited inter-area mode and system brittleness index (SBI) with respect to the excited mode are evaluated without any need to system model. When the SBI exceeds a pre-specified threshold value, it implies that the system is in an emergency condition in which controllers are no longer capable for damping the unstable inter-area mode. It means that the system has become more brittle and vulnerable for