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Decomposition–coordination strategy to improve power transfer capability of interconnected systems

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ABSTRACT

The maximum power transfer across critical corridors or interfaces is limited by various system constraints such as thermal, voltage, and stability limits. In an open transmission access environment, these constraints would be deeply influenced by the interactions among the path flows in different control areas. In particular, small signal stability, commonly in the form of low frequency oscillations, is considered a crucial factor since it limits the power transfer capability of transmission paths in interconnected multi-area systems. Based on such considerations, the focal point of this paper will be a new approach to coordinating the path transfers across multiple control areas, giving exclusive attention to the small signal stability. The differential eigenvalue method is used to derive the damping ratio constraints for satisfying the small signal stability criteria which are linear inequality constraints expressed in terms of the control parameter. Using Bender's decomposition, the proposed methodology is formulated as a master problem and a set of sub-problems, each associated with one area motivated by the improvement of the overall computational efficiency via parallel processing. The performance of the decomposition–coordination method is illustrated with a 68-bus system from which it might be deduced that inter-area transfer margin could be improved by reasonable rescheduling of the neighboring tie-line flows.

1. Introduction

The deregulation in the electricity market leads to higher loading of the transmission network, resulting in the operations of power systems that require many sophisticated forms of security constraints to be met during a variety of possible operational conditions. These include static constraints such as thermal limits of the circuits as well as dynamic constraints, for example voltage, transient, and small signal stability limits. By and large, the dynamic constraints of a system may become more restrictive than the static limits, depending on its operational conditions. Most prominently, a good knowledge of the effects of violating these constraints is very important in operating the system closer to its stability limits by preventing the vulnerable states and obeying the allowable system's operational ranges.

Since a modern power grid consists of multiple entities interconnected tightly with each other [1], interconnected multi-area systems undergo the processing of more transactions across different control areas as the power systems get more stressed with increasing or varying loads. Thus, a power system interconnected with multiple areas needs to be operated in a coordinated manner for maintaining the overall system reliability and ensuring economic operation although each area has its own system operator. Moreover, interconnected multi-area systems are usually decomposed into areas based on various criteria and the operations and control of the whole network of interconnections are undertaken by all the ISOs responsible for their respective areas. To keep the security of the network at a desired level, a higher level of coordination among the ISOs is indispensable and, at the same time, it is necessary to evaluate the path transfer capability by considering the interactions with all the other parts of the entire power grid.

Because of the inherent tradeoff between increasing utilization of the grid and security of the operation, various mathematical techniques using optimal power flow (OPF) have been employed for enhancing the transfer capability without violating dynamic security constraints [2–4]. Traditionally, researches in the area of dynamic security have fully focused on voltage and transient stability. Attempts to provide practical models for OPF subject to voltage and transient stability constraints have been aimed towards the development of new methods for calculating the transfer capability; in this regard, many methods have been developed [5–8]. With the increased generation capacities, different areas in the power system network are combined with their own inertias, making the system prone to inter-area oscillations. As a result, the issue

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of small signal stability, especially the damping of inter-area oscillations, is becoming increasingly crucial since the undamped or poorly damped inter-area oscillations may in fact jeopardize the operational performance. Recently, diverse power transfers through the transmission system with high degree of vulnerability related to small signal stability accounted for system-wide blackout, for instance, the 1996 WSCC events. [9]. As the physical phenomena involved in inter-area oscillations extend over the whole geographical area spanned by the power system, unacceptable inter-area oscillation became a limiting factor for achieving further increases in the transfer capability of interconnected grids. It is generally taken for granted that damping levels of the inter-area modes should restrict the possibility of transferring more power over specified transmission lines by requesting the curtailment or cancelation of the power transfers as an emergency procedure. For the most part, recent work has tended to center around some specific transmission paths within a single control area [10–16]. Coordination across several areas has largely been ignored due to the different ownership of these paths. Since modern electric systems are tightly integrated networks, strictly speaking, the actions of single entity have critical impacts on multiple adjacent systems. Above all, in order to realize a reliable and economical electrical supply, the small signal stability of interconnected grids needs to be examined in determining the power transfer levels between individual areas.

This paper attempts to propose a new strategy for solving an optimization problem when there is an urgent need to improve the path capability of major transmission paths by rescheduling other paths and satisfying rigorous requirements on the small signal stability. For example, the focus will be on maximizing the transfer capability over the critical interface by coordinating other path-flows that have massive impacts on the power transfer across critical interfaces. Based on the theory of differential eigenvalue method, the damping ratio constraints have been incorporated into the proposed method. Bender's decomposition is applied to partition the formulation with the required damping ratio constraints. The optimization problem is decomposed into a master problem and sub-problems for each area and it will be solved concurrently using the primal-dual interior point method (PDIPM). By dividing the sub-problems along the boundary of the interconnected areas, the decomposition–coordination method facilitates the application and it requires less complicated analysis and smaller computing capabilities. The procedure also suggests adjustable re-dispatch of other transmission paths to increase the transfer capability of the critical path under highly stressed operating conditions and then the inter-area transfer margin will be offered after the decomposition–coordination process.

2. OPF model for interconnected multi-area system

The OPF problem has originally been designed for a single-area system [17] and the proposed OPF model will extend the single-area OPF framework to the general interconnected multi-area case. The notation used in this model is as follows:

A	Set of the interconnected areas
M	Set of total number of buses
C	Set of buses with controllable generation
B	Set of boundary buses
L	Set of total number of transmission lines
Ω_i	Set of buses connected to the bus i via the transmission line/transformer
Ω_c	Set of tie-lines belonging to the critical interface
Ω_B	Set of tie-lines joining buses connected to boundary buses
$\mathbf{z} = [\mathbf{x}\ \mathbf{p}]^T$	Vector of the decision variables
$\mathbf{x}$	Vector of state variables
$\mathbf{p}$	Vector of control variables
f	Objective function representing the system's operating costs
$\mathbf{G}(\bullet)$, $\mathbf{H}(\bullet)$	Vector function representing load flow constraints and operating constraints, respectively
P_{gi}, Q_{gi}	Real and reactive power generations at bus i, respectively
P_{li}, Q_{li}	Real and reactive power demands at the load bus i, respectively
P_{ij}, Q_{ij}	Real and reactive power flows from bus i and bus j, respectively
V_i	Voltage magnitude at bus i
G_{ij}, B_{ij}	Real and imaginary parts of the ijth element of the system admittance matrix
θ_{ij}	Voltage angle differences between bus i and bus j
P_{gi}^{min}, P_{gi}^{max}	Lower and upper limits of the real power generation at bus i, respectively
Q_{gi}^{min}, Q_{gi}^{max}	Lower and upper limits of the reactive power generation at bus i, respectively
S_{ij}^{min}, S_{ij}^{max}	Lower and upper limits of the MVA transmission line capacity of line ij, respectively
V_i^{min}, V_i^{max}	Possible lower and upper limits of voltage magnitude at bus i, respectively

In a compact form, the interconnected multi-area OPF problem is described below [18].

$$\begin{aligned} & Min\, f_a(\mathbf{z}_a) \\ & s.t.\, \mathbf{G}_a(\mathbf{z}_a) = \mathbf{0}, \quad a = 1, 2, \cdots, A \\ & \quad \mathbf{H}_a(\mathbf{z}_a) \le \mathbf{0}, \quad a = 1, 2, \cdots, A \\ & \quad \sum_{a=1}^{A} \mathbf{W}_a \mathbf{z}_a = \mathbf{0} \end{aligned} \tag{1}$$

where the subscript a denotes the index of area. Here, $\mathbf{z}_a$ contains both the states variable in each area a of the whole system, such as the bus voltage magnitude and phase angle, and the control variables, i.e., the real and reactive power generation levels, voltage control settings, etc. The last set of constraints in (1) called coupling constraint forces the variables on both areas of the boundary to be the same, where the elements of $\mathbf{W}_a$ are either 0 or 1.

This problem is a typical form of the OPF problem which has an objective of minimizing the total operating costs of the spatially separated generating units in the whole interconnected system respecting a set of equations that characterize the power interchange between areas and the normal operational constraints. However, the main objective of the proposed procedure is to maximize the transfer capability over the tie-lines belonging to the critical interface with no violations of the system constraints. In our work, the critical interface as a portion of the network will be chosen on the basis of a prediction of a potential vulnerability of the system when there is a possibility that the inter-area power transfer can increase in the short term. Since the power transfer has to be maximized, the objective function of (1) reduces to

$$Max \sum_{t \in \Omega_c} P_t \tag{2}$$

The equality constraints, $\mathbf{G}_a(\mathbf{z}_a)$, correspond to the power flow equality constraints; there are two equations for each bus of the global system, representing the real and reactive power balances