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Adaptive real-time congestion management in smart power systems using a real-time hybrid optimization algorithm

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ABSTRACT

In deregulated power systems, where a short period of service interruption causes extreme financial and social damages to customers and service providers, it is necessary to develop optimal intelligent algorithms in order to minimize unforeseen service interruptions due to unavoidable real-time contingencies. Nowadays, regarding the high implementation of communication infrastructure in smart power systems, as well as accurate sensors for a variety of purposes, it is possible to effectively collect and analyze real-time and synchronized data, run fast intelligent algorithms and send control commands to controllers. This paper proposes an adaptive real-time congestion management (RTCM) method which optimally employs adaptive thermal ratings of transmission lines to manage real-time congestions using all power system capabilities. This algorithm is considered as an essential ancillary service in a power market, where all generation companies and customers can participate. In this algorithm, a demand response program is modeled and also a real-time hybrid optimization algorithm is developed to solve the RTCM problem aimed at finding the optimal solution during a short time span. Incorporating an adaptive artificial neural network along with a modified particle swarm optimization (PSO) algorithm is proposed in this paper as a real-time hybrid optimization method. Advantages and effectiveness of this method are demonstrated by numerical results from analyzing the modified 39-bus New England system.

1. Introduction

Real-time transmission congestion management (RTCM) is defined as real-time remedial actions to eliminate congestions from power transmission systems securely [1]. The deregulated structure of power systems also makes it essential to manage real-time congestions through an open market, where all market players are able to participate in ancillary services [2–5]. Although system operators (SO) always try to manage the congestions in day-ahead and hour-ahead energy markets, real-time contingencies are always probable during the operation time. Since power systems are almost highly loaded due to daily demand increments, real-time contingencies could cause insecure situations from the operational point of view. These situations are called real-time congestions and all remedial actions which are done to prevent the system from collapsing are called RTCM. An effective RTCM method should be able to optimally remove the congestion by using all power system capabilities and guide the system to a new operational point considering all power system constraints [6]. There are some cost-free and non-cost free tools in power systems for this purpose. Using the capability of flexible AC transmission system (FACTS) devices and transformers' tap changers, could be considered as cost-free methods while generation rescheduling and demand response program are called non-cost free methods for the RTCM problem [7,8]. Usually, the RTCM problem consists of an optimization problem aimed at minimizing the congestion management cost. For example, in Ref. [9], an optimal rescheduling scheme has been proposed based on the PSO algorithm. The proposed method calculates transmission lines' sensitivities with respect to generators' active power variations and uses these value to minimize the RTCM cost regarding the generators' bid prices. In Ref. [1], a comprehensive RTCM algorithm has been presented which not only uses the quasi-dynamic thermal rating of transmission lines to increase transmission system thermal capacity, but also tries to apply load shedding program in critical congestion situations where rescheduling is not able to manage the congestion independently. Although real-time constraints (e.g. Generators' ramp rates and congestion clearing time) have been modeled in the RTCM problem, the cost-free methods have not been modeled in the proposed RTCM formulation. Furthermore, only classical methods have been used to solve the optimization problem, therefore, it is highly probable that solution algorithm finds just a local

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solution for the problem. Besides that, the proposed algorithm is aimed at removing the congestion from transmission system during a pre-defined clearing time considering the amount of initial congested line current in the post-contingency condition. Although the algorithm divides the congestion clearing time into subsequent subintervals to evaluate the power system variations during the rescheduling process, it does not consider the thermal adaption of conductors during the RTCM process.

In Ref. [6], phase shifter transformers (PST) have been modeled in the RTCM problem as a cost-free method. Results showed that the incorporation of PSTs' operation in the RTCM problem not only could reduce the RTCM cost, but also in some critical congestion cases, the feasible solution for the problem is not available unless PSTs participate in the RTCM problem. Authors have used the PSO algorithm to solve the RTCM problem in an appropriate solution time, the PSO's parameters have been determined based on the trial and error method, which is not a suitable method for real-time applications.

In this paper, an adaptive RTCM algorithm is proposed considering the thermal adaption of transmission lines to manage the congestion optimally. In this method, the demand response program (DR) is modeled in the RTCM algorithm to create an actual RTCM market, where all market players would be able to participate in it. Developing a hybrid real-time search algorithm as a powerful solution tool for the RTCM optimization problem, including an adaptive artificial neural network (AANN) and a modified PSO algorithm, is another issue which is discussed in this paper.

The rest of the paper is organized as follows. Section 2 presents the nomenclature of the paper. In Section 3, the RTCM formulation is presented. In Sections 4 and 5, concepts of adaptive thermal rating and adaptive RTCM method are discussed respectively. Section 6 is dedicated to the proposed real-time hybrid optimization algorithm. The proposed adaptive RTCM algorithm is presented in Section 7. Finally, numerical results are reported and discussed in Section 8 and conclusions are summarized in Section 9.

2. Nomenclature

A. Parameters	
B_{ci}	Coefficients for upper and lower bands in the i-th iteration of the PSO.
C_g	Energy bidding price for the g-th generator ($/MW min).
C_L	Energy bidding price for the L-th load ($/MW min).
C_p	Conductor thermal capacity (J/kg °C).
D_R	Binary input indicating the demand response participation.
GS_g^j	Active power sensitivity of j-th line with respect to the active power variation of the g-th generator.
I_0	The initial value of the conductor current (A).
It_i	The i-th iteration in the PSO.
It_{Max}	Maximum number of iteration in the PSO.
K_T^j	Active power sensitivity of j-th line with respect to the phase shifting variation of the T-th PST.
LS_L^j	Active power sensitivity of j-th line with respect to the active power variation of the L-th load.
m	Mass per unit length of the conductor (kg/m).
Ng	Number of generators.
NL	Number of loads.
N_{line}	Number of transmission lines.
Np	Number of PSTs.
P_g^0	Initial active power set point of the g-th generator (MW).
P_g^{Max}	Maximum operational limit for the g-th generator's active power (MW).
P_g^{Min}	Minimum operational limit for the g-th generator's active power (MW).
P_j^0	Post-contingency active power flow in the j-th line (MW).
P_j^{LTR}	Maximum value for the active power in the j-th line with respect to the LTR level of the conductor current (MW).
P_j^{Max}	Maximum value for the active power in the j-th line (MW).
P_j^{STR}	Maximum value for the active power in the j-th line with respect to the STR level of the conductor current (MW).
P_L^0	Initial active power of the L-th load (MW).
P_L^{Max}	Maximum amount of the L-th load (MW).
P_L^{Min}	Minimum amount of the L-th load (MW).
P_{Size}	Population size of the PSO.
R	Conductor resistance (ohm/m).
t_{cc}	Actual congestion clearing time (min).
T_0	The initial conductor temperature (°C)
T_{cc}^{Max}	Maximum time span for the congestion clearing time (min).
T_{Max}	Maximum conductor temperature (°C).
T_s	The time required to solve the optimization problem (s).
R_g^{Down}	Ramp down rate of the g-th generator (MW/min).
R_g^{Up}	Ramp up rate of the g-th generator (MW/min).
$\Delta\Phi_T^{Max}$	Maximum achievable phase shifting for T-th PST (°).
$\Delta\Phi_T^{Min}$	Minimum achievable phase shifting for T-th PST (°).
u_g	Binary input indicating the g-th generator participation in the RTCM.
u_L	Binary input indicating the L-th load participation in the RTCM.
B. Functions	
q_c	Convection heat loss of the conductor (W/m).
q_r	Radiation heat loss of the conductor (W/m).
q_s	Solar heat rate of the conductor (W/m).
C. Variables	
I	Conductor current (A).
T_c	Conductor temperature (°C).
ΔP_g	Change in the active power of the g-th generator (MW).
ΔP_j	Active power flow variation in the j-th line (MW).
ΔP_L	Change in the active power of the L-th load (MW).
$\Delta\Phi_T$	Change in the phase shifting of the T-th PST (°).

3. RTCM formulation

In Ref. [1], a comprehensive RTCM formulation has been presented considering generators' rescheduling and load shedding tools and in Ref. [6], this formulation has been improved by adding the PSTs' operation into the optimization problem. In this paper, a market-based RTCM formulation is presented which uses DR instead of load shedding as illustrated below:

$$min\left(\sum_{g=1}^{Ng} u_g.C_g.|\Delta P_g| + D_R.\sum_{L=1}^{NL} u_L.C_L.|\Delta P_L|\right) \tag{1}$$

Subject to:

$$(P_j^0 + \sum_{g=1}^{Ng} u_g.GS_g^j.|\Delta P_g| + D_R.\sum_{L=1}^{NL} u_L.LS_L^j.|\Delta P_L| + \sum_{T=1}^{Np} K_T^j.\Delta\Phi_T) \le P_j^{Max} \quad j = 1, 2, 3, \ldots, N_{line} \tag{2}$$

$$\left(P_g^{Min} - P_g^0\right) \le \Delta P_g \le \left(P_g^{Max} - P_g^0\right) \quad g = 1, 2, 3, \ldots, Ng \tag{3}$$

$$\left(R_g^{Down}.t_{cc}\right) \le \Delta P_g \le \left(R_g^{Up}.t_{cc}\right) \quad g = 1, 2, 3, \ldots, Ng \tag{4}$$

$$\left(P_L^{Min} - P_L^0\right) \le \Delta P_L \le \left(P_L^{Max} - P_L^0\right) \quad L = 1, 2, 3, \ldots, NL \tag{5}$$

$$\Delta\Phi_T^{Min} \le \Delta\Phi_T \le \Delta\Phi_T^{Max} \quad T = 1, 2, 3, \ldots, Np \tag{6}$$

$$\sum_{g=1}^{Ng} u_g.\Delta P_g - D_R.\sum_{L=1}^{NL} u_L.\Delta P_L = 0 \tag{7}$$

where

$$t_{cc} = T_{cc}^{Max} - T_s \tag{8}$$

Eq. (2), shows the transmission line active power due to generation rescheduling, DR and PSTs' phase shifting. The sensitivity factors in Eq. (2), are defined as below:

$$GS_g^j = \frac{\Delta P_j}{\Delta P_g} \quad j = 1, 2, 3, \ldots, N_{line} \quad g = 1, 2, 3, \ldots, Ng \tag{9}$$

$$LS_L^j = \frac{\Delta P_j}{\Delta P_L} \quad j = 1, 2, 3, \ldots, N_{line} \quad L = 1, 2, 3, \ldots, Nload \tag{10}$$