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Planning of multi-type FACTS devices in restructured power systems with wind generation

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ABSTRACT

Many electrical power systems are changing from a vertically integrated entity to a deregulated, open-market environment. This paper proposes an approach to optimally allocate multi-type flexible AC transmission system (FACTS) devices in restructured power systems with wind generation. The objective of the approach is to maximize the present value of long-term profit. Many factors like load variation, wind generation variation, generator capacity limit, line flow limit, voltage regulation, dispatchable load limits, generation rescheduling cost, load shedding cost, and multilateral power contracts are considered in problem formulation. The proposed method accurately evaluates the annual costs and benefits obtainable by FACTS devices in formulating the large-scale optimization problem under both normal condition and possible contingencies. The overall problem is solved using both Particle Swarm Optimization (PSO) for attaining optimal FACTS devices allocation as main problem and optimal power flow as sub optimization problem. The efficacy of the proposed approach is demonstrated for modified IEEE 14-bus test system and IEEE 118-bus test system.

Introduction

The rapid technological progress causes the consumption of electric energy increases continuously. Building of new transmission lines (TLs) is difficult for environmental and political reasons. Hence, the power transmission systems are driven closer to their limits endangering the system security [1]. When a TL becomes congested, more expensive generating units may have to be brought on one of its sides. In a competitive market, this causes different locational marginal prices (LMPs) in the two sides. The difference in LMPs between the two ends of a congested TL is related to the extent of congestion and power losses on this line [2]. To ensure secure and economic operation, properly located and sized flexible ac transmission system (FACTS) devices offer an effective means [3]. During normal state, they can relieve congestion, increase voltage stability, increase system loadability, minimize transmission loss, minimize the compensations for generations re-scheduling, minimize the LMPs difference, implying to maximize social welfare. During contingency states, the devices are firstly utilized to secure the system and to minimize operating cost. Then, if violations still persist, generation re-scheduling and load shedding will be carried out to maintain system security under all conditions.

FACTS devices can be connected to a TL in various ways, such as in series, shunt, or a combination of series and shunt. The static VAR compensator (SVC) and static synchronous compensator (STATCOM) are connected in shunt. The static synchronous series compensator (SSSC) and thyristor controlled series capacitor (TCSC) are connected in series. The thyristor controlled phase shifting transformer (TCPST) and unified power flow controller (UPFC) are connected in series and shunt combination [4]. Compensation by FACTS enhances the real power handling capacity of a TL at a much lower cost than building a new line. FACTS devices accomplish smooth control of power over a wide range to support the TL [5]. They have to be located and sized properly to be effective [3]. The techniques used for optimal placement of FACTS devices can be broadly classified into two methods:

(i) *Index-based method:* the priority list is formed to reduce solutions space based on sensitivity indexes with respect to each line and bus [6–10].
(ii) *Optimization-based method:* use either conventional or heuristic optimization methods such as simulated annealing (SA), genetic algorithm (GA), Tabu search (TS), or Particle Swarm Optimization (PSO) [11–16]. The objective function can be single or multi-objective optimizing certain technical/economic operational goals [17,18].

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Nomenclature

B, C	consumer benefit and generation cost respectively
D,G	set of demands and generators, respectively
i, j	bus indices
k	symbol indicating under contingency state
K_s	variable used to represent system losses related to the stressed loading condition
M	set of location candidates for TCSC
N	set of location candidates for SVC
r	the bilateral transaction index
o	symbol indicating under normal state
t	load level
U	set of location candidates for UPFC
B_{SVC}	the susceptance of the SVC at the voltage of 1 p.u.
$c_{1x}, c_{1x,\max}$	installed capacity and maximum capacity of FACTS device candidate at location x
C^k	operating cost under contingency state
C^o	operating cost under normal state
C_{LS}	compensation paid to demand for decreasing active power.
C_{SVC}	SVC investment cost per KVar-installed
C_{TCSC}	TCSC investment cost per KVar-installed
C_{UPFC}	UPFC investment cost per KVar-installed
C_{wi}	The wind power generation cost
C_{GD}^{up}	compensation paid to generator for increasing active power
C_{GD}^{down}	compensation paid to generator for decreasing active power
IC_{dev}	investment cost of FACTS devices
I_G	the set of injection buses for bilateral transaction
J_D	the set of extraction buses for bilateral transaction
N_g	the set of pool and multilateral generators
N_L	the set of pool and multilateral loads
N_W	the set of wind power generation units
P_G	active power generation
P_D,Q_D	the active and reactive pool power demand, respectively
$P_{Gr,i}$	the total real power for multilateral injections at bus i
$P_{Dr,j}$	the total real power for multilateral extractions at bus j
P_{wi}	the power generated by wind generator at bus i
$Q_{Gr,i}$	the total reactive power for multilateral injections at bus i
$Q_{Dr,i}$	the total reactive power for multilateral extractions bus i
P_{Li}^k	real power of dispatchable load part at bus i for the kth contingency
Q_{Li}^k	reactive power of dispatchable load part at bus i for the kth contingency
S_{SVC}	SVC capacities in MVar
S_{TCSC}	TCSC capacities in MVar
S_{UPFC}	UPFC capacities in MVar
X_{line}	the reactance of the transmission line between bus i and j
X_{TCSC}	the reactance contributed by TCSC
r_{TCSC}	the degree of compensation of TCSC
ΔP_g	generation re-scheduling vector ($\Delta P_g = 0$ at normal state)
ΔP_d	load shedding vector ($\Delta P_d = 0$ at normal state)
ΔP_G^{up}	active power generation adjustment up
ΔP_G^{down}	active power generation adjustment down
ΔP_D^{down}	Active power demand adjustment down
λ	load margin ($\lambda = 0$ at current loading condition)
–	symbol indicating under stressed loading condition

Many recent studies have focused on FACTS devices allocation considering voltage stability and congestion relief. Refs. [6,7] have proposed optimal allocation methods for TCSC to eliminate the line overloads against contingencies, where sensitivity index called *single* contingency sensitivity (*SCS*) is introduced for ranking the optimal placement. In [8], an index developed by reactive power spot price has been used for optimal allocation of SVC. Priority list method based on the LMPs is used in [9] to reduce solutions space for TCSC allocation for congestion management. Ref. [10] has proposed a technique to recover the investment cost of TCSC for congestion management in deregulated electricity markets. The proposal evaluates the benefits of TCSC and converts them into monetary values. It is based on increase in generator and load surplus due to use of TCSC. In [11], the FACTS devices location problem is solved by means of GA to lower the cost of energy production and to improve the system loading margin. In [12], the same problem is formulated as a mixed-integer nonlinear programming problem. The optimal placement is obtained by optimizing both the investment cost in FACTS and the security in terms of the cost of operation under contingency events. Ref. [13] has proposed an improved solution using the multi-start Benders decomposition technique to maximize the loading margin of a transmission network through the placement of SVCs. In [15], PSO technique is presented to seek the optimal places of TCSC, SVC and UPFC in power system. The objectives of optimization are minimizing the cost of FACTS installation and improving the system loadability. It is obvious from the achieved results that the system loadability cannot be enhanced further after locating specific number of FACTS devices. However, economic feasibility analysis is not included in that paper. In [16], a meta-heuristic technique such as non-dominated sorting PSO optimization (NSPSO) has been used to find optimal locations of FACTS devices to maximize loading margin, reduce real power losses, and reduce load voltage deviation.

Almost all of the reported methods have not explicitly taken into account both the normal state and contingency state operation analysis in the FACTS allocation problem. Also, the compensations for generations re-scheduling are not addressed at various operating conditions. Furthermore, the appropriate market model is mostly missing. This paper proposes a new approach for optimal allocation of FACTS devices in restructured power system integrating wind generation. The objective is to maximize the annual profit under both normal and contingency operation, meanwhile maintaining system stability and security. This implies to: minimize devices investment cost, minimize the LMPs difference between buses, and maximize benefit due to devices installation. The problem is formulated as a large-scale optimization problem. In addition, dynamic state transitions caused by specified contingencies are also included in the optimization problem. Several load and wind generation levels representing distinctive conditions are used in the analysis. The formulated optimization problem is highly nonlinear and mixed integer problem. PSO is utilized for determining FACTS devices locations and capacities, while optimal power flow (OPF)-based optimization is used to determine operating cost. The proposed method is applied to modified IEEE 14-bus and IEEE 118-bus systems.