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

A. Elmitwally *, A. Eladl

Elect. Eng. Dept., Mansoura University, Mansoura 35516, Egypt

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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].

* Corresponding author. Tel.: +20 050 2300779; fax: +20 050 2244690.
E-mail address: kelmitwally@yahoo.co.uk (A. Elmitwally).

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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.

Facts model

For static applications, FACTS devices can be modeled by two methods: (i) Power Injection Model (PIM), (ii) Impedance Insertion Model (IIM). The power injection model handles the FACTS as a device that injects a certain amount of active and reactive power to a node. The impedance insertion model represents the FACTS devices as known impedance inserted to the system in series, shunt or combination of them according to the device type. These methods do not destroy the symmetrical characteristic of the admittance matrix and allows efficient and convenient integration of FACTS devices into existing power system analytical software tools [9,10]. This paper focuses on the optimal location and settings of three kinds of FACTS, namely the SVC, TCSC, and the UPFC. They are chosen because of their fast control responses, low investment costs and ability to increase loadability as discussed in [11,19].

Model of SVC

The SVC is a shunt compensator that may have two modes: inductive or capacitive [11]. The SVC combines a capacitor bank shunted by a thyristor-controlled reactor as shown in Fig. 1a. In this paper, the SVC is modeled as a variable admittance as in Fig. 1b.

The reactive power provided is limited as given in (1).

$$S_{SVC} = -V_i^2 \times B_{SVC} \tag{1}$$

and

$$B_{SVC\,\min} \leqslant B_{SVC} \leqslant B_{SVC\,\max} \tag{2}$$

Model of TCSC

The TCSC is a series compensation component which consists of a series capacitor bank shunted by a thyristor-controlled reactor as in Fig. 2a. The basic idea behind power flow control with the TCSC is to vary the overall line's effective series impedance, by adding a capacitive or inductive impedance [16,20]. The TCSC is modeled as a variable impedance as depicted in Fig. 2b. After installing TCSC, the new reactance of the line is estimated by (3).

$$X_{ij} = X_{line} + X_{\mathrm{TCSC}} = r_{\mathrm{TCSC}} \cdot X_{line} \tag{3}$$

To avoid overcompensation, X_{TCSC} is set between $-0.7\ X_{\mathrm{line}}$ (capacitive) and $0.2\ X_{\mathrm{line}}$ (inductive) [20].

Model of UPFC

Basically, the UPFC consists of series and shunt voltage source inverters. These two inverters share a common DC-link. They are connected to the power system through two coupling transformers. The basic structure of UPFC is shown in Fig. 3. The UPFC can control the voltage, impedance, phase angle, real and reactive power flow in a TL. The voltage drop on the line can be regulated by the shunt converter of UPFC and the power flow is controlled by the series converter [21].

The UPFC can have a coupled model or a decoupled model. For the coupled model, UPFC is modeled as two series combinations of a voltage source and an impedance. One of them is series connected to the TL. The second is shunt connected to the line. The two combinations are coupled through the UPFC control system. For the decoupled model, the above two voltage source-impedance combinations are independent [22]. The first model is more complex compared to the second one because modification of Jacobian matrix in coupled model is inevitable [21]. Decoupled model can be easily implemented in conventional power flow algorithms without modification of Jacobian matrix. In this paper, decoupled model is used for modeling UPFC.

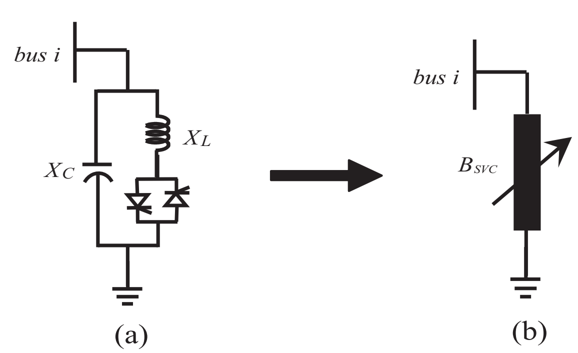

Fig. 1. Static var compensator (a) basic structure, (b) model.

Problem formulation

The problem is composed of two levels, the FACTS devices sizing and location sub-problem (upper level) and operation cost estimation sub-problem (lower level). The problem includes both normal and contingency states. The upper level sub-problem is to determine locations and capacities of FACTS devices. The lower level sub-problem is an OPF-based problem to obtain minimum operating cost of each state incorporating FACTS devices given by the upper level. Then, the operating costs, as a component of the total annual cost, are fed back to the upper level. The iterative process is repeated until a termination criterion is satisfied.

In this paper, the annual load growth rate is assumed as a fixed value of 5%. Typically, yearly load pattern is clustered into several load levels. Three load levels, 100%, 75%, and 50% of yearly peak load, are considered in the daily load duration curve as revealed in Fig. A1.

Many restructured utilities in the world have considerable penetration levels of renewable resources, particularly wind energy. Increasing penetration of renewable resources in the electric grid is expected to have significant impact on transmission operation and planning. So, the power system is assumed to have an integrated wind generation in this analysis. The power from renewable resources, like wind and solar, is highly stochastic in nature. The daily wind generator output power is assumed to have various levels of output as depicted in Fig. A1. Wind generation is assumed to grow by 5% yearly. Wind power generation is generally treated as a negative load in power system studies. This is to indicate their capability for delivering current meanwhile their voltage is imposed by the electrical system at the connection point [23].

Main problem

The difference between the annual generation costs and the annual revenue of loads is called the expected benefit (*EB*). The average present values are used in calculating EF. So, EF is rather the average present value of the annual profit of the power system. This value is always negative because the revenue from loads is greater than the generation costs. Both normal and contingency states are considered on computing *EB*. Before installing FACTS devices, *EB* is denoted as $EB_{without\ \mathrm{FACTS}}$. It is denoted as $EB_{with\ \mathrm{FACTS}}$ after installing FACTS devices. Hence, $EB_{with\ \mathrm{FACTS}}$ depends on locations and capacities of installed FACTS devices as detailed in Secti on 'Operation cost sub-problem'.

The main objective function of FACTS devices optimal allocation in restructured power system is formulated as follows:

$$Minimize \quad Total\ Cost = AIC_{dev} + (EB_{\text{with FACTS}} - EB_{\text{without FACTS}}) \tag{4}$$

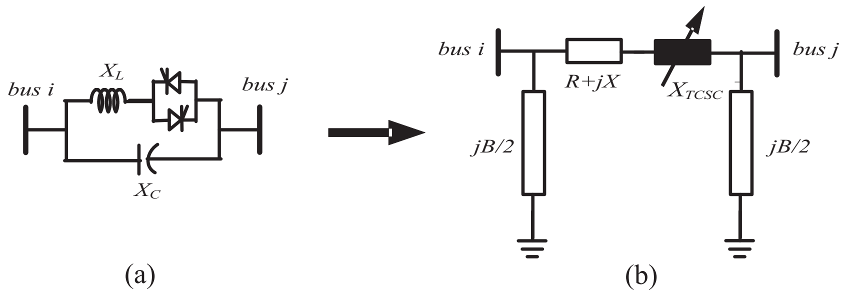

Fig. 2. Thyristor controlled series compensator (a) basic structure, (b) model.

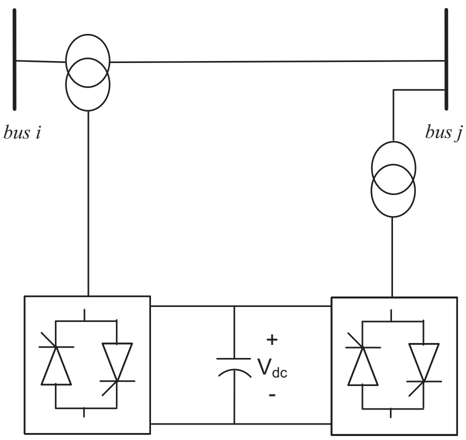

Fig. 3. The basic structure of UPFC.

AIC_{dev} is the average present value of annual FACTS devices investment cost. $EB_{without\ \mathrm{FACTS}}$ is assumed already optimum and constant. The first term in (4) is determined by number and capacities of installed FACTS devices as explained in Section 'FACTS devices investment cost'.

Subject to:

Power balance equation for any node i,

$$p(V_i^k, \theta_i^k, C^k) = P_{\mathrm{Gi}}^k + P_{wi}^k - P_{\mathrm{Li}}^k + P_{\mathrm{Gr},i} - P_{\mathrm{Dr},i} \tag{5}$$

$$\mathrm{q}(V_i^k, \theta_i^k, C^k) = Q_{\mathrm{Gi}}^k + Q_{\mathrm{wi}}^k - Q_{\mathrm{Li}}^k + Q_{Gr,i} - Q_{Dr,i} \tag{6}$$

Generator capacity constraints,

$$P_{\mathrm{Gi\ min}} \leqslant P_{\mathrm{Gi}}^k \leqslant P_{\mathrm{Gi\ max}}, \quad Q_{\mathrm{Gi\ min}} \leqslant Q_{\mathrm{Gi}}^{\mathrm{ok}} \leqslant Q_{\mathrm{Gi\ max}} \tag{7}$$

Dispatchable load constraints,

$$P_{\mathrm{Li\ min}} \leqslant P_{\mathrm{Li}}^k \leqslant P_{\mathrm{Li\ max}}, \quad Q_{\mathrm{Li\ min}} \leqslant Q_{\mathrm{Li}}^k \leqslant Q_{\mathrm{Li\ max}} \tag{8}$$

Bus voltage constrains,

$$V_{i\,\mathrm{min}} \leqslant V_i^k \leqslant V_{i\,\mathrm{max}} \tag{9}$$

Line flow constraints,

$$|\mathrm{MVA}_{ij}| \leqslant \mathrm{MVA}_{ij\,\mathrm{max}} \tag{10}$$

Bilateral/multilateral power balance,

$$\sum_{i \in I_G} P_{Gr,i} = \sum_{j \in J_D} P_{Dr,j} \tag{11}$$

Constraints for generation re-scheduling and load shedding,

$$P_{Gi}^k = P_{Gi}^0 + \Delta P_{Gi}^{up,k} - \Delta P_{Gi}^{down,k}, \quad P_{Dj}^k = P_{Dj}^0 - \Delta P_{Dj}^{down,k} \tag{12}$$

$$\Delta P_{Gi}^{up,k}, \quad \Delta P_{Gi}^{down,k}, \quad \Delta P_{Dj}^{down,k} \geqslant 0 \tag{13}$$

Constraints to satisfy minimum loading margin,

$$\bar{\lambda}^k \geqslant \lambda_{\mathrm{min}} \tag{14}$$

Demand and generation increase direction:

$$\begin{aligned} \overline{P}_{Gi}^k &= P_{Gi}^k(1 + \bar{\lambda}^k + K_s) \\ \overline{P}_{Dj}^k &= P_{Dj}^k(1 + \bar{\lambda}^k) \\ \overline{Q}_{Dj}^k &= Q_{Dj}^k(1 + \bar{\lambda}^k) \end{aligned} \tag{15}$$

Constraints in (15) are intended to express coupling between normal and contingency states. Also, it is a way to ensure that compensations are always positive values. In case of contingency, demands have no option to increase their power exceeding the power demand determined in normal state.

FACTS devices investment cost

The range of cost of major FACTS devices is presented in Siemens AG Database [19]. A polynomial cost function of FACTS devices is derived and used for FACTS allocation study as in [3,11]. The investment costs of TCSC and SVC can be formulated as follows:

$$\dot{C}_{\mathrm{TCSC}} = 0.0015\,S_{\mathrm{TCSC}}^2 - 0.713\,S_{\mathrm{TCSC}} + 153.75 \tag{16}$$

$$\dot{C}_{SVC} = 0.0003\,S_{SVC}^2 - 0.3051\,S_{SVC} + 127.38 \tag{17}$$

$$C_{\mathrm{UPFC}} = 0.0003\,S_{\mathrm{UPFC}}^2 - 0.2691\,S_{\mathrm{UPFC}} + 188.22 \tag{18}$$

$$\begin{aligned} IC_{dev} = &\sum_{m \epsilon M} S_{\mathrm{TCSC},m} \times C_{\mathrm{TCSC},m} + \sum_{n \epsilon N} S_{SVC,n} \times C_{SVC,n} \\ &+ \sum_{u \epsilon U} S_{\mathrm{UPFC},u} \times C_{\mathrm{UPFC},u} \end{aligned} \tag{19}$$

Constraint of FACTS devices is given as follows:

$$0 \leqslant c_{lx} \leqslant c_{lx,\mathrm{max}} \tag{20}$$

Then, the following expression is used to convert the investment cost into annual term:

$$AIC_{dev} = IC_{dev} \times \frac{ir(1+ir)^{LT}}{(1+ir)^{LT} - 1} \tag{21}$$

where ir is interest rate and LT is lifetime of FACTS device.

Market model

In this study, a hybrid market model is considered. A voluntary central pool is the most likely arrangement that will emerge in practical restructured power system [10]. This pool will set the price of bilateral and/or multilateral transactions [24]. The generation companies (GENCOs) submit a bid curve (supply bid) to independent system operator (ISO) and distribution companies (DISCOs) has the flexibility to submit either price-elastic demand (with benefit bid curve) or fixed demand. The bilateral/multilateral transaction holders request transaction of power specifying the points of injection and points of extraction. They pay the energy charge based on the difference in LMP at the points of injection

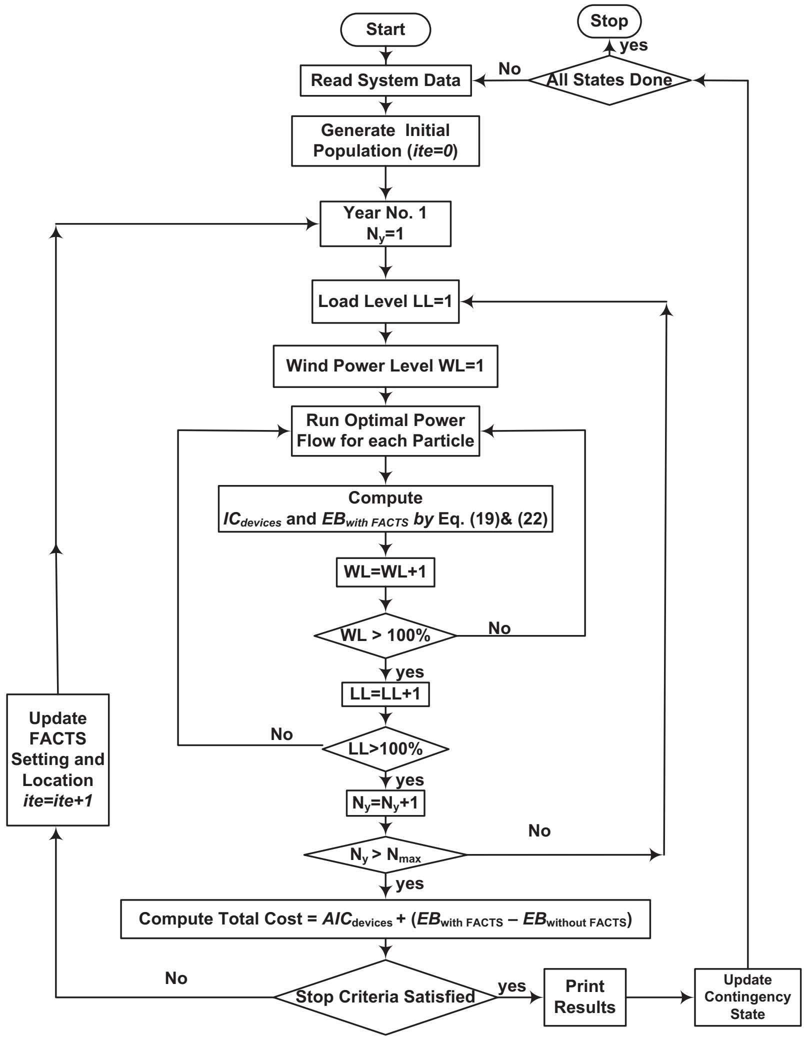

Fig. 4. Flowchart of the solution algorithm.

Table 1
Optimal locations and capacities of FACTS devices under normal state.

Location	TCSC (MVAR)		SVC (MVAR)		UPFC (MVAR)	
	Line 7–9	Line 13–14	Bus 9	Bus 14	Series Line 6–11	Shunt Bus 11
Capacities	0.6287	0.2882	15.9249	25.6863	2.8719	24.7951

Table 2
Optimal locations and capacities of FACTS devices under contingency states.

Contingency line		Required capacity (MVAR)					
		TCSC		SVC		UPFC	
From	To	Line 7–9	Line 13–14	Bus 9	Bus 14	Series Line 6–11	Shunt Bus 11
1	2	0.1645	0.1792	28.34	5.45	2.90	28.02
2	3	0.923	0.6666	29.12	27.88	2.67	28.88
2	5	0.0079	0.2436	0.0	2.01	1.2086	0.0
4	5	0.0067	0.0085	27.40	28.19	2.7589	28.95
4	7	0.0715	0.2185	22.61	18.50	0.0352	26.05
4	9	0.0367	0.0874	27.09	28.70	1.5549	29.15
5	6	0.0	0.0024	1.80	0.0	2.6817	11.02
10	11	0.073	0.2436	24.87	28.05	2.2817	29.05
12	13	0.0001	0.2436	29.16	24.95	2.7653	28.95
13	14	0.0131	0.0147	24.01	21.88	0.8151	28.67

Table 3
Average operating cost in various states for 100% and 75% load levels.

Contingency line		Load level 100%						Load level 75%					
		Social welfare ($/h)		Generation re-scheduling cost ($/h)		Load shedding cost ($/h)		Social welfare ($/h)		Generation re-scheduling cost ($/h)		Load shedding cost ($/h)	
From	To	Without FACTS	With FACTS	Without FACTS	With FACTS	Without FACTS	With FACTS	Without FACTS	With FACTS	Without FACTS	With FACTS	Without FACTS	With FACTS
Normal state		−5947.5	−8358.8	0	0	0	0	−1861.8	−1879.7	0	0	0	0
1	2	−4372.9	−8123.1	541.92	7.55	236,270	0.0	−1792.3	−1903.8	124.83	11.13	4547.6	0.0
2	3	−5955.2	−8414.2	343.84	6.77	167,660	0.0	−1993.9	−2005.4	58.76	5.79	2598.3	0.0
2	5	−7807.1	−7780.7	1409.7	469.4	485,400	371,140	−2178.1	−2089.1	229.72	68.80	38,103	2107
4	5	−5876	−8293	125.53	7.78	131,690	0.0	−1878.9	−1880	17.87	2.48	0.0	0.0
4	7	−5719.8	−8407.9	146.93	22.75	183,440	0.0	−1797	−1936.3	10.64	2.81	0.0	0.0
4	9	−6421.3	−8306.2	134.22	16.93	93,849	0.0	−1873.6	−1960.2	20.26	1.95	3099.3	0.0
5	6	−9038.2	−6474	908.8	483.01	324,500	19,584	−2034.8	−1969.8	362.78	42.12	45,960	4155
10	11	−5916.5	−8233.4	57.72	7.72	108,930	0.0	−1871.4	−1875.1	20.70	1.626	0.0	0.0
12	13	−5936.9	−8279.2	19.58	7.71	32,541	0.0	−1861.9	−1865.4	0.64	0.16	0.0	0.0
13	14	−10,899	−8332.9	1282.6	7.61	445,520	0.0	−1822.1	−2074.9	79.41	3.73	24,796	0.0

Table 4
Average annual cost/benefit of system operation.

No.	Items	Amount ($/year)
1	Average annual social welfare with FACTS devices	−43360491.32
2	Average annual social welfare without FACTS devices	−28397356.98
3	Increase in social welfare due to FACTS devices	14963134.34
4	Average annual cost of FACTS devices	1993216.6
5	Net increase in social welfare due to FACTS devices	12969917.74

and extraction. Based on the submitted bids by GENCO and DISCO, and considering the bilateral/multilateral transactions, the ISO solves the security-constrained OPF to find the optimum dispatch [25].

Operation cost sub-problem

$EB_{with\,\mathrm{FACTS}}$ includes the system operating cost and loads revenue under normal and contingency states. It is aimed to minimize the operating cost of each state by optimally utilizing the FACTS devices with their capacities specified by the upper level sub-problem. In order to minimize the operating cost, each state is thus formulated as an OPF problem incorporating voltage stability criteria. $EB_{with\,\mathrm{FACTS}}$ is given as follows:

$$EB_{with\,\mathrm{FACTS}} = \sum_{t=1}^{T}\pi^{(0,t)}C^{(0,t)} + \sum_{t=1}^{T}\sum_{k=1}^{K}\pi^{(k,t)}C^{(k,t)} \tag{22}$$

where $C^{(0,t)}$ and $C^{(k,t)}$ are hourly operating benefit of normal state and contingency k for load level t, respectively; $\pi^{(k,t)}$ is product of frequency and duration of contingency k in a year for load level t. The duration of all contingency states and normal state is 8760 h/year. $C^{(o,t)}$ is formulated as follows:

$$C^{(o,t)} = \sum_{i=1}^{Ng}C_i(P^o_{Gi}) + \sum_{i=1}^{Nw}C_{wi}(P^o_{wi}) - \sum_{i=1}^{Nl}B_i(P^o_{Di}) \tag{23}$$

It is assumed herein that the generating units and loads submitted bids are the true marginal cost and the true marginal benefit, respectively. Then, ISO clears the energy market based on those bids. Lagrange multiplier associated with real power balance equations obtained from OPF after installing of FACTS devices will become market clearing price [3].

When a contingency state occurs, corrective actions such as FACTS devices control (as a cost-free means), generation re-scheduling, and load shedding (as non-cost-free means) are utilized to avoid line overload, voltage instability and maintain load margin. Generation companies receive compensations for changing the output power to non-optimal value. If load shedding should be executed, demands will also be compensated for their interrupted load during contingency [26]. The operating benefit during contingency in (22) $C^{(k,t)}$ includes social welfare, compensations due to generation re-scheduling and load shedding. Participating generators that increase their power output will be compensated for providing reserve power. Meanwhile, generators decreasing their power output will also obtain compensations for lost opportunity cost [3]. $C^{(k,t)}$ is formulated as follows:

$$C^{(k,t)} = \sum_{i=1}^{Ng}C_i(P^k_{Gi}) + \sum_{i=1}^{Nw}C_{wi}(P^o_{wi}) - \sum_{j=1}^{Nl}B_j(P^k_{Dj}) + \sum_{i=1}^{Ng}\left(C^{up}_{GD}\Delta P^{up,k}_{Gi} + C^{down}_{GD}\Delta P^{down,k}_{Gi}\right) + \sum_{j=1}^{Nl}C_{LS}\Delta P^{down,k}_{Dj} \tag{24}$$

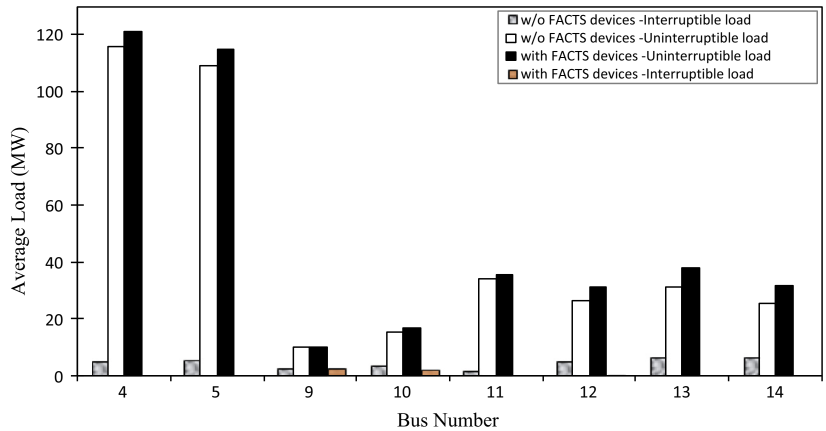

Fig. 5. Interruptible and uninterruptible load without and with FACTS devices (load level 100%).

Solution algorithm

The overall problem is formulated as a two-level hybrid large scale mixed integer nonlinear programming problem solved by hybrid PSO-sequential quadratic programming (SQP) method. The upper level is solved using standard PSO [27,28]. Locating FACTS devices is a discrete problem. Determining devices capacities is a continuous problem. The outcomes of the upper level is passed to the lower level (operation sub-problem). This sub-problem is composed of multiple states. Each state is classified as a continuous problem. It is formulated as an OPF problem solved by SQP. Matpower version 4.1 [29] is used to solve each state problem. The lower level will provide the upper level with $EB_{with\,\mathrm{FACTS}}$ component of the fitness function.

The proposed solution algorithm is described below.

Step 1: Define line and bus data of the power system, contingency data (frequency and duration of each contingency), all operational constraints, and PSO parameters.
Step 2: Generate an initial population of particles with random positions and velocities representing location and size of FACTS devices.
Step 3: Set iteration index $ite = 0$.
Step 4: For each particle, update bus data (for SVC and shunt part of UPFC) and line data (for TCSC and series part of UPFC) based on its locations and setting values. Determine the load level and wind output power. Conduct OPF incorporating FACTS devices, for normal and contingency states. Compute the operating cost and required devices capacities for each state.
Step 5: Calculate $EB_{\mathrm{with\ FACTS}}$ using operating costs of all states and their associated probabilities to occur. Calculate devices investment cost using (8).
Step 6: Evaluate the value of the fitness function (4). Check all the constraints. If any of the constraints is violated, a penalty term is applied. The calculated value of the fitness function is served as a fitness value of a particle.
Step 7: Compare the fitness value of each particle with the personal best, *Pbest*. If the fitness value is lower than *Pbest*, set this value as the current *Pbest*, and save the particle position corresponding to this *Pbest* value.
Step 8: Select the minimum value of *Pbest* from all particles to be the current global best, *Gbest*, and record the particle position corresponding to this *Gbest* value.
Step 9: Update the velocity and position of all particles.
Step 10: If the maximum number of iterations is reached, the particle associated with the current *Gbest* is the optimal solution. Otherwise, set $ite = ite + 1$ and return to Step 4.
Step 11: End.

Fig. 4 depicts the flowchart of the solution algorithm.

Case studies and results

The proposed solution algorithm is coded as one entity in MATLAB environment. The effectiveness of proposed approach will be illustrated using the IEEE 14-bus and 118-bus test systems.

IEEE 14-bus system

The modified IEEE 14-bus system is used to evaluate the proposed approach. Detailed data of generators, demand, and lines limits are given in Appendix A [29]. The system includes a wind generator at bus 8. There is also a multilateral transaction of 35 MW between the seller S at bus 6 and two buyers B at bus 9 and bus 14. This transaction holder has requested ISO to provide transmission access to transmit power from bus 6 to bus 9 and bus 14. It is assumed that the load at each bus including the multilateral transaction grows with an annual rate of 5%. The wind generator output power increases at an annual rate of 5% as well. The planning time period is taken as 10 years. The determined optimal locations and capacities of FACTS devices under normal operating conditions are presented in Table 1.

The required capacities of FACTS devices under various contingency states are shown in Table 2. It is worthy noting the determined locations of FACTS devices for all contingency states are the same as the normal state. Also, it is observed that the highest FACTS setting occurs when the contingency line is 2–3. The overall optimal set of FACTS devices for both normal and contingency states can be identified as:

$$S_{n,l} = \sum_{k=1}^{M} S_{n,l}^{k} p_k$$

where $S_{n,l}$ is the size of the *n*th type device at possible location l. $S_{n,l}^{k}$ is the determined size of the *n*th type device at possible location l for the *k*th state (normal or contingency). p_k is probability of occurrence of the *k*th state. M is the number of possible states.

The operating cost consists of social welfare, generation rescheduling, and load shedding costs. Table 3 manifests the operating cost for each operation state before and after installing FACTS. 100% and 75% load levels are compared in Table 3. Outages of lines (2–5), (5–6) and (13–14) cannot be counterbalanced by re-setting of FACTS devices. As a result, operating cost during those contingencies with FACTS devices is higher than the base case.

Congestion relief and loss reduction contribute to the social welfare improvement under normal state. Moreover, it is observed that load shedding can considerably be reduced in almost all of contingency states. Social welfare improvement during load level 75% is less significant than that during load level 100%, but load shedding can be avoided for all contingency states. Generally, installing FACTS increases the delivered load and improves system security. So, it improves social welfare [5–10].

Table 4 shows the average annual cost/benefit of system operation, without and with FACTS devices.

Fig. 5 gives the uninterruptible average loads (over 10 years) at individual buses without and with FACTS devices. It is evident that FACTS devices utilization improves loadability as it increases amount of uninterruptible average loads. Shed part of interruptible average load at almost all buses is eliminated except very small amount of interruptible load at bus 9 and bus 10. It is noted that the shed part of all interruptible loads is zero up to the 5th year of the planning period. Starting from the 6th year, a small amount of interruptible loads is shed at buses 9 and 10. This is due to that the power system is highly stressed by increasing loads. So, line congestion and impermissible voltage drop can not be eliminated without load shedding under this very high load condition.

Figs. 6 and 7 describe the detailed load shedding and generation re-scheduling without and with FACTS devices. Load shedding and generation re-scheduling are significantly reduced by optimal installation of FACTS devices. Load shedding is eliminated under most of contingency states. However, under critical contingencies at lines (2–5) and (5–6), the FACTS devices can not avoid a small amount of load curtailment. Power generation re-scheduling also considerably decreases under all contingency cases due to optimal installation of FACTS devices.

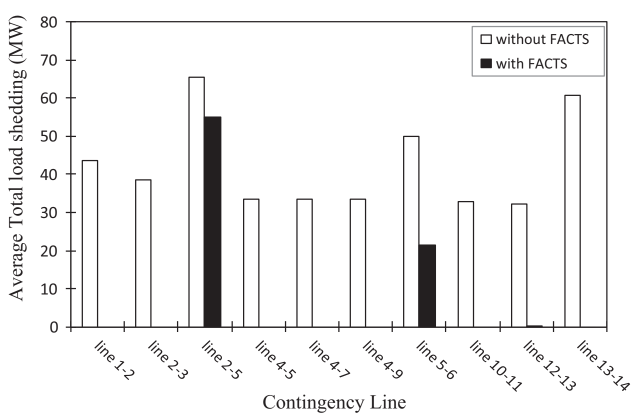

Fig. 6. Average total load shedding under various contingencies (load level 100%).

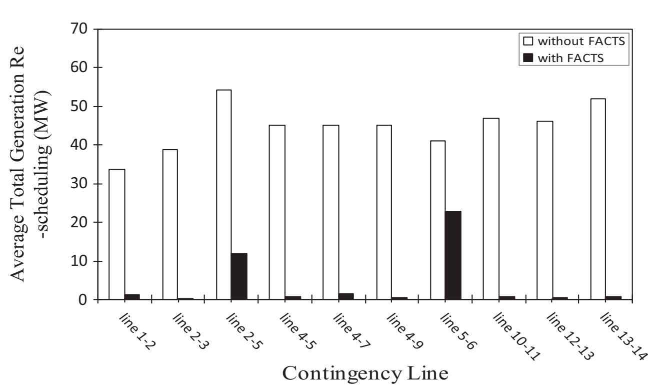

Fig. 7. Average total generation re-scheduling under various contingencies (load level 100%).

Fig. 8 gives the relation between the actually-served load and years. It can be seen that, the system is always able to accommodate the monotonic yearly increase in the load with the favor of optimally installing FACTS devices. There is no need to expensive transmission and/or generation expansions. On the other hand, without FACTS devices, the system can only accommodate the monotonic yearly increase up to the 5th year of the planning period. Then, expensive transmission and/or generation expansions are inevitable.

Fig. 9 presents the relation between social welfare and years. It can be remarked that the social welfare from the system is much higher owing to installing FACTS devices. This is attributed to the fact that FACTS improves the economics of system operation and greatly increases its loadability.

Fig. 10 shows the bus voltage profile with and without FACTS devices. It can be seen that, when FACTS devices are properly installed in the system, the voltage of all buses are improved. Fig. 11 presents the power flow in transmission lines. The power flow in most transmission lines increases after installing FACTS devices increasing system loadability.

Effect of wind generator

In this section, the effect of wind generator in the normal state operation of the system will be discussed. There are four cases for the operation of the system as follows:

(i) *The system contains the wind generator with FACTS devices:* the social welfare is $8358.8, and the lowest voltage in the tenth year is 0.9865 p.u and occurs at bus 5. No congestion occurs.

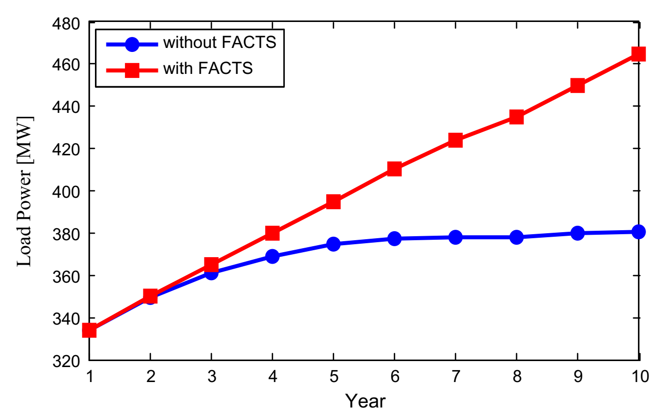

Fig. 8. Average total load for each year (load level 100%).

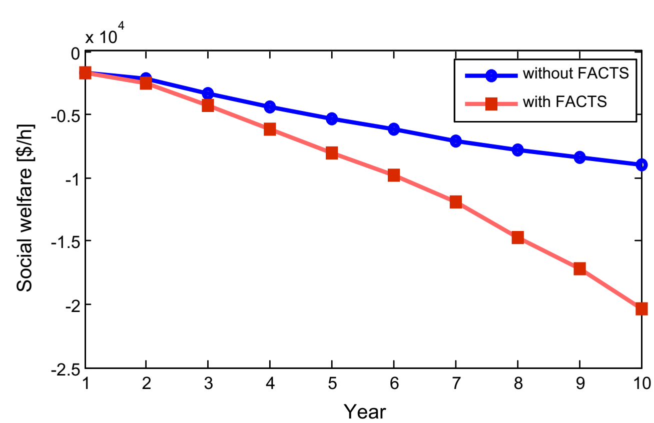

Fig. 9. Average social welfare for each year (load level 100%).

(ii) *The system contains the wind generator without FACTS devices:* the social welfare is \$5947.5, and the lowest voltage in the tenth year is 0.95 p.u and occurs at bus 14. Congestion occurs in lines (4–5) and (10–11).
(iii) *The system does not contain wind generator but FACTS devices:* the social welfare is \$7454.9, and the lowest voltage in the tenth year is 0.999 p.u and occurs at bus 5. The congestion occurs in lines (10–11) and (4–5).
(iv) *The system does not contain wind generator or FACTS devices:* the social welfare is \$5485.7, and the lowest voltage in the tenth year is 0.95 p.u and occurs at bus 14. The congestion occurs in the line (10–11).

From the above it can be concluded that the presence of wind generator leads to increase of social welfare especially with FACTS devices. Also, it can cause congestion in some lines. Inclusion of FACTS devices in the power system can significantly mitigate this congestion.

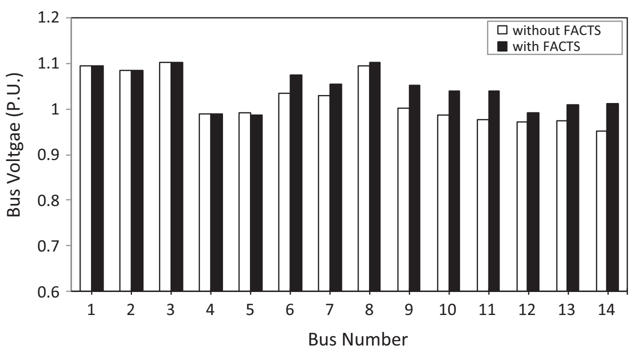

Fig. 10. Bus voltage (at load level 100% and wind power level 100%).

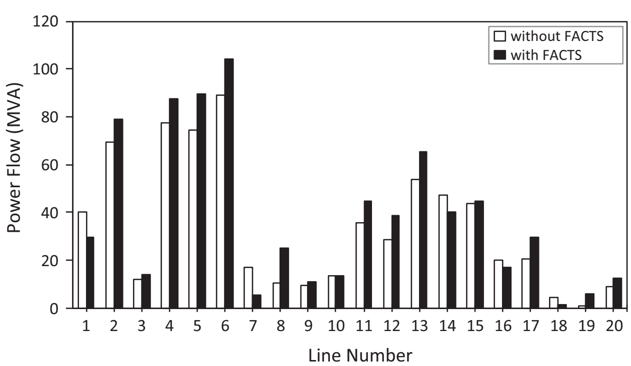

Fig. 11. Line power flow (at load level 100% and wind power level 100%).

IEEE 118-bus system

In order to show the applicability of the proposed algorithm in large scale systems, a modified IEEE118 bus test system is used. The system consists of 54 generator buses, 99 loads and 186 branches (TLs plus transformers). The bus data and line data values are taken from [29]. The system contains two wind generators at bus 37 and 38. Simulations are carried out for optimal location and capacity for mixed-type FACTS devices. It is assumed that there are 25 FACTS devices available for the system (this number was chosen because the improvement of system loadability not improved after this number) [11]. Table 5 shows the suitable location and size of multi-type FACTS devices. By installing those devices, the annual cost saving is \$10272138 for normal operation state at 100% of load level.

Conclusion

This paper presents an approach to optimally allocate multiple FACTS devices in deregulated electricity market environment. The proposed approach is based on a comprehensive cost model that considers the annual cost of FACTS devices, operation cost, and customer benefit. The effect of wind generation and load growth are addressed. The task is formulated as a two-level mixed-integer nonlinear optimization problem. The annual net cost is taken as the objective function. Bus voltage limits, line flow limits, generator capacity limits are the main constraints. Hybrid Particle-swarm and sequential quadratic programming-based OPF are employed to solve the optimization problem. The impacts of the optimally allocated FACTS devices includes increasing social welfare and reducing the compensation paid to market participants due to generation re-scheduling and load shedding.

Appendix A

Setting of parameters and constants used in simulation are given as follows:

(1) The MVA limits of transmission lines are three times of base case line flow. The voltage limits are 0.95 and 1.1 p.u. All loads have constant power factor of 0.9 lagging.
(2) Number of PSO particles is 40 and number of iterations is 100. Parameters c_1, c_2, ω_{max} and ω_{min} used in PSO are 1, 1, 0.9, and 0.4, respectively.
(3) Maximum equivalent reactance of TCSC is assumed between $-0.7\ X_{\text{line}}$ (capacitive) and $0.2\ X_{\text{line}}$ (inductive), while maximum installed capacity of SVC is 0.3 pu. The capacity range for UPFC is the same as for TCSC and SVC.
(4) Interest rate and life time of devices are assumed to be 0.04 and 15 years, respectively.

Table 5
Suitable locations and capacities of FACTS devices for IEEE 118-bus system.

No.	TCSC		SVC		UPFC			
	Location	Capacity (MVAR)	Location	Capacity (MVAR)	Series location	Capacity (MVAR)	Shunt location	Capacity (MVAR)
1	37–39	−1.5895	94	1.11	86–87	−0.2022	87	18.44
2	18–19	−0.1013	109	1.77	38–65	−9.8024	65	13.75
3	103–110	−0.3957	95	12.86	76–118	−0.0134	118	6.04
4	33–37	−0.6707	10	21.64	38–37	−8.193	37	15.22
5	55–56	−0.0144	50	2.3335	35–36	−0.0066	36	7.77
6	15–19	−0.0029	92	18.46	75–77	−0.0963	77	17.82
7	64–65	−0.9441	107	13.76	49–66	−7.8394	66	1.51
8	82–96	−0.1749	81	11.25	95–96	−0.0913	96	24.12
9	5–11	−5.2589	21	5.81	14–15	−0.0014	15	9.75
10	91–92	−0.0507	73	5.18	39–40	−0.0065	40	22.38

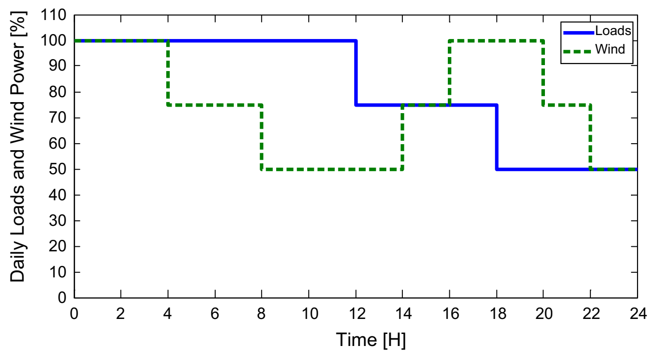

Fig. A1. Daily variation of loads and wind availability.

Table A1
Generator data.

No.	Bus no.	P (MW)		Q (MVAR)		Cost coefficient		
		Max	Min	Max	Min	C_2	C_1	C_o
1	1	100	0.0	40	0.0	0.245	10	0.0
2	2	500	0.0	50	0.0	0.351	10	0.0
3	3	500	0.0	50	0.0	0.389	10	0.0
4	6	100	0.0	50	0.0	0.372	10	0.0
5	8	0.0	0.0	25	0.0	–	–	–

Table A2
Pool demand data.

No.	Bus no.	P (MW)		Maximum interruptible load (MW)	Cost coefficient		
		Min	Max		C_2	C_1	C_o
1	4	95	142.5	47.5	−0.15	100	0.0
2	5	90	135	45	−0.15	100	0.0
3	10	15	22.5	7.5	−0.15	100	0.0
4	11	28	42	14	−0.18	120	0.0
5	12	25	37.5	12.5	−0.18	120	0.0
6	13	30	45	15	−0.18	120	0.0

Table A3
Multilateral contract data.

No.	Bus no.	Type	Min P (MW)	Cost coefficient		
				C_2	C_1	C_o
1	6	Seller	35	−0.15	100	0.0
2	9	Buyer 1	10	−0.15	100	0.0
3	14	Buyer 2	25	−0.15	100	0.0

(5) C_{GD}^{up} and C_{GD}^{down} are 0.4 of power price in normal state. Meanwhile, C_{LS} is $10838 per MW h-curtailed load [3].
(6) The duration of load levels 100%, 75%, and 50% are assumed to be 12, 6, and 6 h per day, respectively. The duration of various contingencies is 240 h per year.
(7) The peak output power of wind generator at bus 8 is 20 MW, and the duration of output levels 100%, 75%, and 50% are assumed to be as shown in Fig. A1. The cost coefficient C_{wi} is $ 20 per MW/h of output power.

Data of generators, demand and multilateral contract are given in Tables A1–A3, respectively.

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