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An approach for increasing wind power penetration in deregulated power systems

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Wind power integration;
FACTS devices;
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Congestion relief;
Voltage stability.

Abstract. Wind power generations as a renewable source of energy have recently gone under the spotlight of policy markets and energy providers. However, the technical constraints, production variability, and uncertainty of wind power have limited its extensive integration into power systems. Having these limitations in mind, the present paper sets a new methodology for increasing wind power integration in deregulated electricity market. The proposed method is presented with the consideration of voltage stability assessment and wind power uncertainties. Our plan aims at maximizing social welfare and minimizing investment and annual operation cost. At the same time, we seek to overcome line constraint by taking wind uncertainties into account. In order to fulfill the aims, FACTS devices and price sensitive loads are utilized. On the other hand, a multi-objective optimization problem is used to evaluate the annual costs and outcomes of wind power investment, the optimal setting of FACTS devices, and optimal load shedding. Expected Security Cost Optimal Power Flow (ESCOPF) is used to minimize the expected total cost of system operation. To solve the proposed planning problem, Non-Dominated Sorting Genetic Algorithm (NSGA-II) is exploited. Our proposed method has been applied to an IEEE30 bus test system by considering two wind scenarios. The simulation results demonstrate the efficiency of the proposed planning.

1. Introduction

1.1. Motivation and approach

The increase in power consumption and intensive usage of transmission systems have led power systems to operate at their security boundaries and have resulted in vulnerability to voltage stability problems. Generally speaking, these limitations are defined by transmission lines constraints and voltage stability limits. They can be overcome by the addition of new generation and transmission facilities and the use of demand-side resources. In restructured power systems, renewable energies such as ancillary services play an important role in ensuring system stability. Recently, wind power generations have been used, but production variability and the uncertainty of wind power has limited their integration into power systems. On the other hand, suitable areas for installation of wind farms can usually be found in areas which are far from the main transmission lines. Transmission systems in these areas might not be able to support new power plants and control voltage stability constraints, especially in critical conditions. Under such conditions where a new production unit is added, if the transmission facilities are not upgraded properly, the power transfer ability of the transmission system becomes impaired by these transfer limitations. Here, providing series compensation for the lines to augment the power-transfer capability, optimal allocation of

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reactive power compensators and using flexible loads appear to be a feasible solution. FACTS devices are fast response devices and can overcome transmission congestion while improving the voltage stability. The potential benefits brought about by FACTS controllers enable them to tackle the deviations of wind power production and reduce wind power spillage. Moreover, because of the variability and forecasted errors of wind generation, load flexibility in the power system can increase the penetration of wind generations. Hence, price-sensitive loads could be an effective solution for increasing load flexibility. This tool can reduce demand on various occasions to maintain the system stability. In addition to the technical constraints of wind power, the eventual future decline and financial risk of it restrict the investment in wind power. Therefore, deciding on compensation without considering financial risks and investment can result in wrong investment decisions, while in deregulated power systems, the profits of market participants and system stability must be maximized.

In this article, a new method for increasing wind power integration into deregulated electricity market is presented. In this method, we use a multi-objective optimization problem considering both technical and economic aspects of power system. To this end, a large-scale optimization problem that contains annual system loading states and wind power generation is used. Our plan aims at maximizing social welfare and minimizing investment and annual operation cost. At the same time, we seek to overcome line constraint by taking wind uncertainties into account. In order to fulfill the aims, FACTS devices and price-sensitive loads are utilized. Among FACTS devices, Thyristor Controlled Switch Capacitors (TCSC) and Static VAr Compensator (SVC) are chosen due to their low investment cost and capability of improving the load ability. On the other hand, ESCOPF is used to minimize the expected total cost of the system operations. Furthermore, the revenue of wind power selling is added to ESCOPF objective function. In order to solve the proposed planning problem, NSGA-II is used. The simulation results are obtained from an IEEE-30 bus test system, and they show the validity of the proposed planning.

It should be noted that wind uncertainties are considered by two wind scenarios which distribute Wind Power Duration Curve (WPDC) during to Load Duration Curve (LDC) according to real patterns. Also, the main objective of transmission planning in deregulated power markets is to provide nondiscriminatory and competitive market conditions to all stakeholders while maintaining power system reliability.

1.2. Literature review and contributions

Wind power is one of the most promising renewable energy resources and is expected to be used more extensively in the future. A big concern over using wind power is the lack of transmission capacity because most wind resources are generally located far from load centers. Therefore, power systems need to be upgraded [1]. Regardless of market conditions, power systems should always be operated in a way that no contingency causes any form of instability [2]. So, it is necessary to evaluate the effect of wind generation on the stability of systems. Reference [3] provides a detailed methodology to assess the impact of wind generation on the voltage stability of power systems. That article shows how the voltage stability margin of power systems can increase through proper application of voltage control strategies to wind turbines. In [4], new methods have been presented to increase wind penetration level by placing new wind generation at voltage stability of strong wind injection buses. The structural voltage stability analysis of a power system integrating wind farm based on induction generators is presented in [5]. In [6], minimizing the amount of imposing load shedding and strengthening the static stability of systems were analyzed by proper sizing and placement of Distributed Generation (DG) units.

Despite the increase in power demand, the expansion of power transmission lines has been rather limited. Due to heavily loaded transmission lines and line constraints, FACTS devices have been used for relieving these lines over loads. A new formulation for FACTS allocation with the purpose of security enhancement against voltage collapse is proposed in [7]. Particle Swarm Optimization (PSO) technique is used in [8] to estimate the feasible optimal setting of TCSC device and enhance the power transfer capability. In [9], Harmony Search Algorithm (HAS) has been applied to an optimal allocation of shunt FACTS devices in a power system to improve power system voltage stability. Some methods to overcome congestion by generation rescheduling together with the installation of FACTS devices and/or load shedding are presented in [10]. Change of the nature of power systems due to the operation of the existing transmission lines closer to their limits, using FACTS devices, and increased penetration of new types of generators have been analyzed in reference [11].

In addition to the above solution, power systems need resources to compensate the wind power generation forecast uncertainty. These resources must be used to maintain real-time balance between production and consumption during the operation of the power system. Demand-side resources could be an effective solution for resolving the mentioned shortcomings. These resources can eliminate the disadvantages of conventional generators by compensating the variations and forecast errors in wind generation. Load shedding and generation rescheduling are used to increase voltage stability and more attention is given to their economic aspects. Reference [12] presents a congestion management algorithm by the optimal rescheduling of the active powers of generators and load power consumptions. The application of computational intelligence techniques for load shedding to power systems is reviewed in [13]. The economic advantages of operating micro-grids with controllable loads are shown in [14].

The main aim of transmission planning in deregulated power markets is to provide nondiscriminatory and competitive market conditions for all stakeholders while maintaining power system stability at the same time [15]. In these markets, the objective functions are different from those in conventional markets. In deregulated markets, concepts such as annual investment cost, social welfare, and nodal prices are considered when dealing with the problem. An efficient and reliable optimization approach to optimal allocation of TCSC in the double-auction power market is presented in [16]; this approach is based on investment cost recovery. In [17], both technical and economic benefits of the installation of TCSC devices are explained by emphasizing generating cost. A risk-constrained multi-stage stochastic programing model is proposed in [18] to make optimal investment decisions with respect to wind power facilities. Compared to new transmission or generation facilities, FACTS devices are currently receiving more attention with respect to overcoming congestion in lines. These devices also enjoy a relatively low investment cost. A few works used these devices for improving the integration of wind power penetration into electrical networks. Most studies on FACTS devices focus on optimal allocation and setting of these devices to fully utilize the transmission capacity, but the economic aspects are not appropriately considered. As a matter of fact, the economic benefits of minimizing wind power spillage have not received enough attention in any of the previous works. In this article, we concentrate on both technical and economic aspects of minimizing wind power spillage.

1.3. Article organization

The rest of this article is organized as follows. Section 2 describes the impact of wind generation on transmission lines. Section 3 explains FACTS devices and the investment cost. Section 4 provides a framework for the proposed approach. Section 5 demonstrates the numerical results of applying the proposed method to an IEEE30-bus test system. Finally, Section 6 brings a conclusion obtained from an experiment reported in this article.

2. The impact of wind generation on transmission lines

The most suitable sites to use the wind resources are located in areas far from conventional power centers and areas with large consumption. If the objective is to make full use of the generated electrical energy, installation of large wind farms in these areas means that it may be necessary to export the produced energy to other places. However, transmission systems in these areas might not be able to support additional power plants. The limitations of transmission lines in these areas also restrict the transmission capacity during extreme situations such as high wind power penetration. Because of these technical issues, great energy spillage could happen (Figure 1). Therefore, when making decision about wind power investment, it is necessary to take heed of transmission limits as an important factor. Such restrictions in the transmission of power are related to the thermal limits of conductors, voltage stability problems, and the transient stability of systems. The possible strategies that can be used to overcome the transmission limits with minimum investment costs include changing the conductor cables, increasing the number of transformers in the existing substations, using FACTS devices to increase the capacity of the lines, and directing the flow to the least loaded lines.

System load is also uncertain and affects the dispatch of wind generators. When the load level is very low, marginal conventional generation costs will also be low, which means that transmission investment to utilize wind power may not be economically proper; therefore, the variation of load should be considered in order to capture wind-incorporated system conditions. For instance, the annual load and wind production data of Pennsylvania, New Jersey, and Maryland Interconnection (PJM) are illustrated in Figures 2 and 3. The data suggest that wind power generation increases when the load decreases and vice versa. In both of these conditions, wind power spillage may arise. In the first condition, due to the excessive wind generation capacity and the limitation of transmission lines, and in the second condition, due to low marginal conventional generation costs, wind power integration into power system may be restricted.

In order to solve this problem, power systems need resources to compensate these wind power generation variations. These resources could be utilized to maintain the real-time balance between production and consumption during the power system operation.

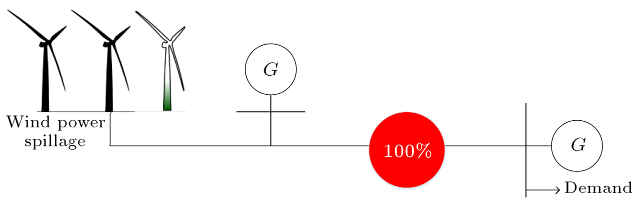

Figure 1. Wind power spillage due to transmission line constraints.

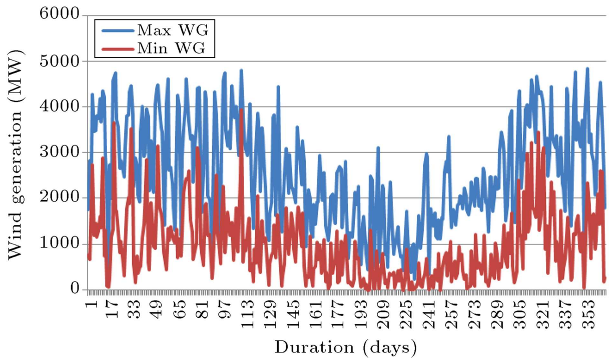

Figure 2. Maximum and minimum daily wind generations in PJM in 2013.

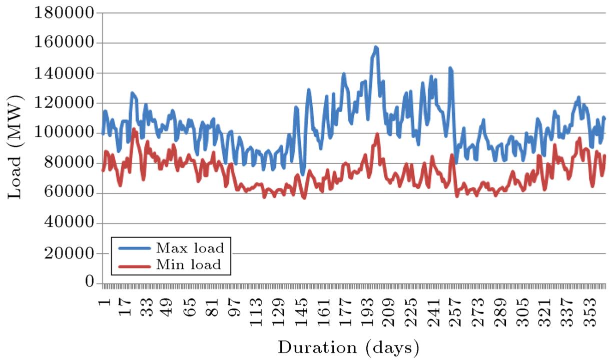

Figure 3. Maximum and minimum daily loads in PJM in 2013.

Demand-side resources could be an effective solution and can eliminate the disadvantages of conventional generators in compensating the variations. They can also predict errors in wind generation.

3. FACTS devices

FACTS devices are power electronic based systems that control AC transmission system parameters. Among FACTS devices, SVC and TCSC are selected in this article due to their technical ability and low investment cost.

SVC is a variable impedance device which consists of a Thyristor Controlled Reactor (TCR) in parallel with a bank of capacitors (Figure 4). SVC is extensively used to provide fast reactive power and voltage regulation support. Increasing power transfer in long lines and improving the stability of system by fast acting voltage regulation are the main technical objectives of the application of SVC in this article. According to [7], the investment cost of SVC can be formulated as follows:

$$C_{\mathrm{SVC}} = 0/0003S_{\mathrm{SVC}}^2 - 0/3051S_{\mathrm{SVC}} + 127/38, \qquad (1)$$

$$IC_{\mathrm{SVC}} = \sum_{n\in N} S_{\mathrm{SVC},n}C_{\mathrm{SVC},n}, \qquad (2)$$

where IC_{SVC} is the Investment Cost of SVC.

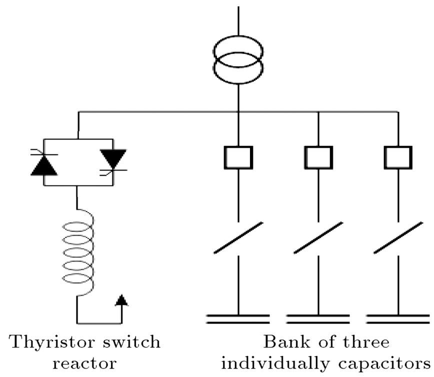

Figure 4. Schematic of static VAr compensator.

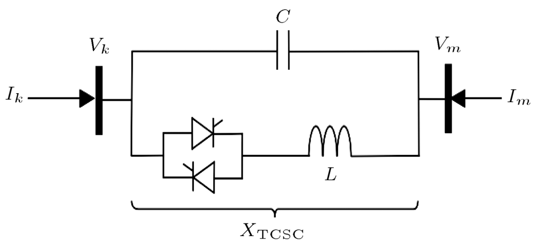

Figure 5. Single-phase Thyristor Controlled Series Capacitor (TCSC).

TCSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a TCR in order to provide a smoothly variable series reactance (Figure 5). Thus, TCSC can change the electrical length of the compensated transmission line, and it can also increase the static stability of the system. The investment cost of SVC can be formulated as follows:

$$C_{\mathrm{TCSC}} = 0/0015S_{\mathrm{TCSC}}^2 - 0/713S_{\mathrm{TCSC}} + 153/75, \qquad (3)$$

$$IC_{\mathrm{dev}} = \sum_{m\in M} S_{\mathrm{TCSC}}C_{\mathrm{TCSC}}, \qquad (4)$$

where IC_{SVC} is the Investment Cost of TCSC.

The total investment cost of these devices can be calculated as follows. In order to convert investment costs into Annual Investment Cost (AIC), the following expression is used:

$$IC_{\mathrm{dev}} = \sum_{m\in M} S_{\mathrm{TCSC}}C_{\mathrm{TCSC}} + \sum_{n\in N} S_{\mathrm{SVC},n}C_{\mathrm{SVC},n}, \qquad (5)$$

$$AIC_{\mathrm{dev}} = IC_{\mathrm{dev}}\frac{ir(1+ir)^{LT}}{(1+ir)^{Lt}-1}, \qquad (6)$$

where ir is the interest rate and LT is the lifetime of FACTS devices.

4. Framework of the proposed method

In electric power systems, technical and economic aspects are not separated from each other. Therefore, it is not appropriate to consider only one of them as an objective function. Thus, in this study, both aspects are addressed. Technical objectives aim to improve the power system operation and economic objectives seek to increase the benefits of all participants. In this article, the minimization of investment cost and annual operating cost, and the maximization of social welfare are considered as economic objectives. Furthermore, satisfying line constraints and increasing the stability of system are considered as technical objective functions. These objective functions are defined as follows.

4.1. Objective functions of the problem

The aims of the proposed planning included: maximizing social welfare, minimizing annual operating cost and investment cost, and satisfying line constraint and voltage stability, at the same time, by taking wind uncertainties into account. Increasing static stability and social welfare maximization are described as below.

Increasing static stability: Increasing the system load ability, considering load generation balance and line overloading constraints is called static stability maximization. The minimum loading margin constraints are as follows:

$$P_L = P_L^0(1+\lambda), \tag{7}$$

$$Q_L = Q_L^0(1+\lambda), \tag{8}$$

where P_L^0 and Q_L^0 are the total active and reactive load powers of the base case, respectively, and λ is the load factor.

Social welfare maximization: Minimizing generation cost and maximizing consumer benefit and wind power revenue are considered as social welfare maximization under normal conditions. The cost function of each generator and benefit function of each demand are considered by a single quadratic function of the generated or consumed power, respectively; for computing the revenue of selling wind power, a proper function including both load level and wind power generation is considered. This revenue, computed as wind power generation, times the Locational Marginal Price (LMP) of the corresponding bus. Therefore, the social welfare can be written as follows:

$$SW^n=\sum_{j\in D} B_j(P_{Dj}^n)+\sum_{t\in WF}\mathrm{LMP}_t.P_{WFt}-\sum_{i\in G} C_i(P_{Gi}^n), \tag{9}$$

where $C(P_{Gi}^n)$ and $B(P_{Dj}^n)$ are the generation cost function and consumer benefit cost function, respectively; LMP_t is the Locational Marginal Price at wind farm t and P_{WFt} is wind power production at wind farm t.

For preserving load-generation balance in each condition, load shedding is sometimes inevitable, especially in critical conditions. In this article, two types of loads have been considered: interruptible and uninterruptible. Interruptible loads are a group of loads which have agreed to have their load subject to interruption in case of critical conditions and this agreement includes compensation for interruption.

Generators with high ramp rates can balance load-generation; however, because of technical issues and high compensation for generators to increase or decrease the active power, minimizing generation rescheduling has been considered as an objective function.

These objective functions have been applied to social welfare under critical conditions and formulated as follows:

$$\begin{aligned} SW^c=&\sum_{j\in D} B_j(P_{Dj}^n)+\sum_{t\in WF}\mathrm{LMP}_t.P_{WFt}-\sum_{i\in G} C_i(P_{Gi}^n) \\ &+\sum_{i\in G}\left(C_{GD}^{\mathrm{up}}\Delta P_{Gi}^{up,c}+C_{GD}^{\mathrm{down}}\Delta P_{Gi}^{\mathrm{down},c}\right) \\ &+\sum_{j\in D} C_{\mathrm{LS}}\Delta P_{Dj}^{\mathrm{down},c}, \end{aligned} \tag{10}$$

subject to:

constraints for generation rescheduling:

$$P_{Gi}^c = P_{Gi}^n + \Delta P_{Gi}^{\mathrm{up},c} - \Delta P_{Gi}^{\mathrm{down},c}, \tag{11}$$

$$P_{Dj}^c = P_{Dj}^n - \Delta P_{Dj}^{\mathrm{down},c}, \tag{12}$$

$$\Delta P_{Gi}^{\mathrm{up},c} \le R_{Gi}^{\mathrm{up}}.\Delta t, \tag{13}$$

$$\Delta P_{Gi}^{\mathrm{up},c} \le R_{Gi}^{\mathrm{up}}.\Delta t, \tag{14}$$

$$\Delta P_{Gi}^{\mathrm{up},c}, \Delta P_{Gi}^{\mathrm{down},c}, \Delta P_{Gi}^{\mathrm{down},c} \ge 0, \tag{15}$$

where C_{GD}^{up} and C_{GD}^{down} are compensations for generator to increase and decrease the active power, respectively; ΔP_G^{up} and $\Delta P_G^{\mathrm{down}}$ are the active power generation adjustment up and down, respectively; R_G^{up} and R_G^{down} are the generation ramping limits for adjustment up and down, respectively; Δt is the time required to adjust the generator output; C_{LS} is the compensation for the demand to decrease active power; and $\Delta P_D^{\mathrm{down},c}$ is the active power demand adjustment up.

4.2. ESCOPF

ESCOPF is a method for computing normal and critical operating points by creating an Optimal Power Flow (OPF) problem where the goal is to minimize the expected cost of system operation [19]. Unlike many OPF models, this model includes consumer benefit as a negative cost in the cost function. In this article, wind power revenue has also been added as a negative cost to the cost function.

The objective function and constraints of ESC are given as follows:

$$\min\left\{\mathrm{ESC}=\sum_{l=1}^{L}\sum_{s=1}^{S}\left[\pi^{n(l,s)}C^{n(l,s)}+\sum_{k=1}^{K}\pi^{k(l,s)}C^{k(l,s)}\right]\right\},\tag{16}$$

$$\sum_{l=1}^{L}\sum_{s=1}^{S}\pi^{n,l}+\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{k=1}^{K}\pi^{k,l}=8760,\tag{17}$$

where n and k represent normal condition and critical conditions, respectively; $C^{n(l,s)}$ and $C^{k(l,s)}$ are the costs of operation in normal and critical conditions in load level l and wind level s, respectively; $\pi^{n,l}$ and $\pi^{k,l}$ are the durations of the corresponding states, respectively.

Subject to pre-contingency equality constraints:

$$P_i^n=P_{Gi}^n-P_{Li}^n,\qquad \forall i,\tag{18}$$

$$Q_i^n=Q_{Gi}^n-Q_{Li}^n,\qquad \forall i,\tag{19}$$

and post-contingency equality constraints:

$$P_i^k=P_{Gi}^k-P_{Li}^k,\qquad \forall i,\tag{20}$$

$$Q_i^k=Q_{Gi}^k-Q_{Li}^k,\qquad \forall i,\tag{21}$$

these equality constraints refer to load generation balance of the buses in normal and contingency states.

Inequality constraints are:

$$X_{\min}^n\le X^n\le X_{\max}^n,\tag{22}$$

$$X_{\min}^k\le X^k\le X_{\max}^k,\tag{23}$$

$$V_{\min}^n\le V^n\le V_{\max}^n,\tag{24}$$

$$V_{\min}^k\le V^k\le V_{\max}^k,\tag{25}$$

$$P_{Gi\min}^n\le P_{Gi}^n\le P_{Gi\max}^n,\tag{26}$$

$$P_{Gi\min}^k\le P_{Gi}^k\le P_{Gi\max}^k,\tag{27}$$

$$Q_{Gi\min}^n\le Q_{Gi}^n\le Q_{Gi\max}^n,\tag{28}$$

$$Q_{Gi\min}^k\le Q_{Gi}^k\le Q_{Gi\max}^k,\tag{29}$$

$$S_{ij}^n\le S_{ij\max}^n,\tag{30}$$

$$S_{ij}^k\le S_{ij\max}^k.\tag{31}$$

Inequality constraints which limit voltage phase angles, transformer tap ratios, and phase shifter angle are included in vector X. The other constraints are voltage magnitude, power injections at each bus, and line capacity in normal and contingency states.

4.3. NSGA-II

NSGA-II is the second version of the famous "Non-dominated Sorting Genetic Algorithm" based on the work of Professor Kalyanmoy Deb. It is used for solving non-convex and non-smooth single and multi-objective optimization problems. The NSGA-II procedure is shown in Figure 6 and explained in the following:

1. First, it randomly initializes the population;
2. Chromosomes are sorted and put into fronts based on Pareto non-dominated sets. Within a Pareto front, the chromosomes are ranked based on Euclidean between solutions or I-Dist (the term used in NSGA-II). Generally speaking, solutions which are far away (not crowded) from other solutions are more often preferred in the selection. This is done in order to make a diverse solution n set and avoid a crowded solution set;
3. The best N (population) chromosomes are picked from the current population and put into a mating pool;
4. In the mating pool, tournament selection, crossover, and mating take place;
5. The mating pool and current population are combined. The obtained set is sorted and the best N chromosomes form the new population;
6. Go to step 2, unless the maximum number of generations is reached;
7. The solution set is the highest ranked Pareto non-dominated set of the latest population.

4.4. The proposed solution

In this article, a multi-objective optimization problem is used to evaluate the optimal setting of FACTS devices and optimal load shedding. We also seek to calculate the annual cost and benefits of FACTS devices installation. ESCOPF is used to minimize the expected total cost of the system operation. The revenue of selling wind power in market is computed as the LMP of the bus, at which the wind power is generated multiplied by the wind power generation. This revenue is added to the ESCOPF objective function. To solve the proposed planning problem, Non-dominated Sorting Genetic Algorithm (NSGA-II) and

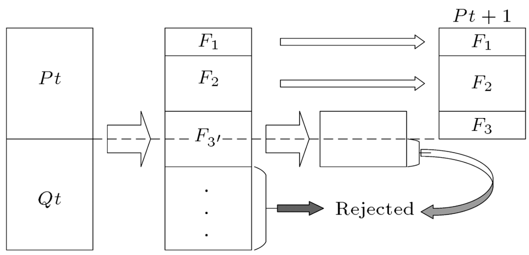

Figure 6. NSGA-II procedure.

a multi-objective constrained nonlinear mixed integer optimization programming are considered (Figure 7).

5. Simulation and results

5.1. Data

To verify the effectiveness of the proposed method, simulation tests were carried out on the IEEE30-bus test system. Two wind farms with maximum wind power production values equal to 35 and 55 MW are located in 16 and 29 buses, respectively (Figure 8). The price-sensitive loads are also put in 4, 7, 10, and 12 buses. The annual wind power capacity data of these wind farms are illustrated in Tables 1 and 2.

In order to model the annual system loading and the wind power generation, LDC (Figure 9) with three load levels and WPDC with twenty levels have been considered. The summation of hourly wind power production of the wind farms has been given in Fig-

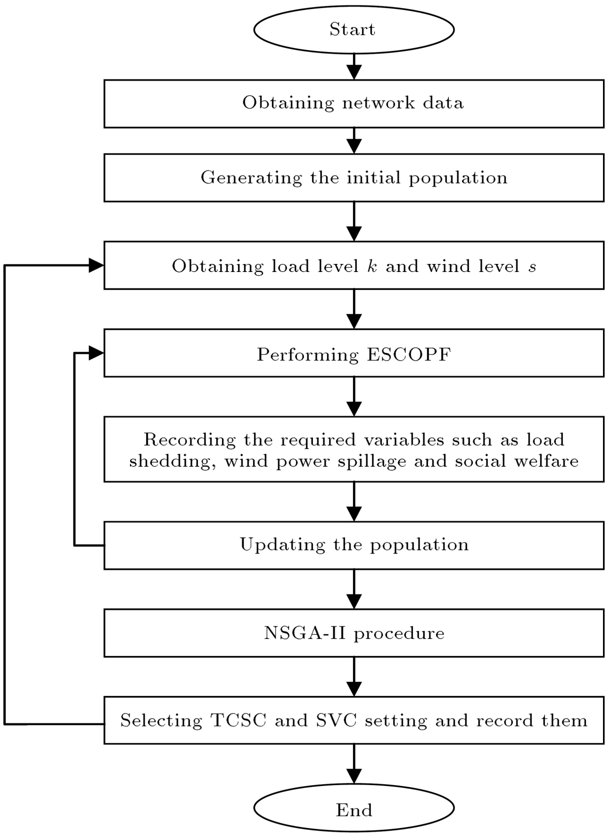

Figure 7. Flowchart of the proposed planning.

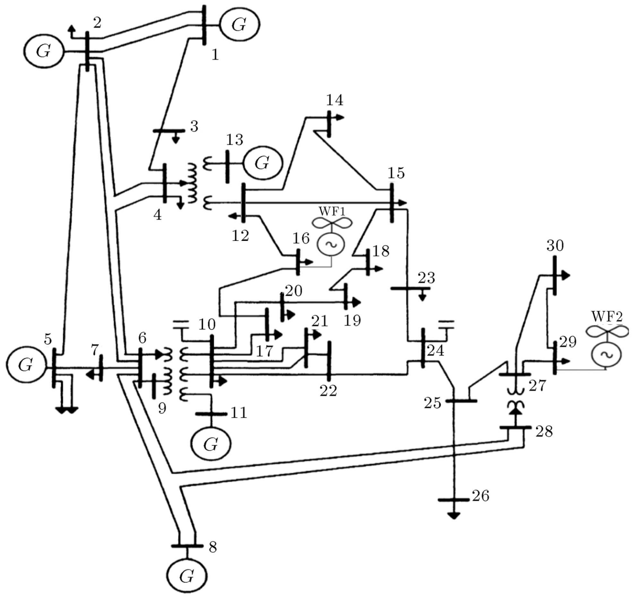

Figure 8. One-line diagram IEEE-30-bus test system with two wind farms.

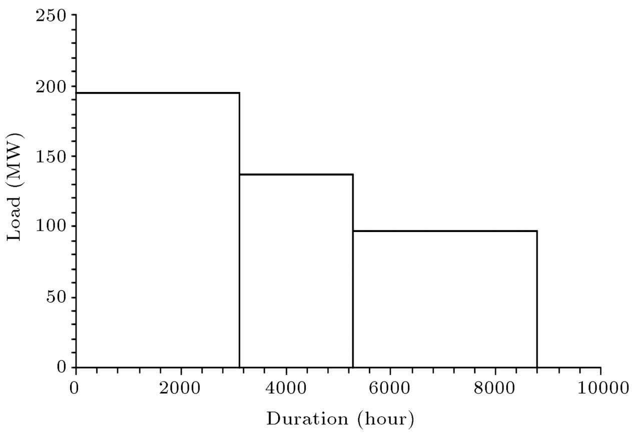

Figure 9. The considered load duration curve.

Table 1. Wind power capacity data of wind farm 1.

Wind power capacity (MW)	Hours in a year
35	1095
32	1752
25	1095
20	1752
18	1533
8	1533

Table 2. Wind power capacity data of wind farm 2.

Wind power capacity (MW)	Hours in a year
55	547.5
45	547.5
40	876
35	547.5
30	876
25	1314
20	1642.5
15	766.5
10	1642.5

ures 10 and 11. These two figures are provided based on real patterns of PJM and according to maximum and minimum of the hourly wind turbine output. These figures also illustrate the WPDC of these wind farms.

To evaluate the proposed method, two scenarios (Figures 12 and 13) that distribute WPDC to LDC have been considered. These two scenarios are assumed based on the maximum and minimum possible hourly wind power capacities of the wind farms.

In order to reduce the computational time, the method in [20] is used for a preliminary analysis of the locations for FACTS device allocation. According to this analysis, the line candidates for TCSC allocation

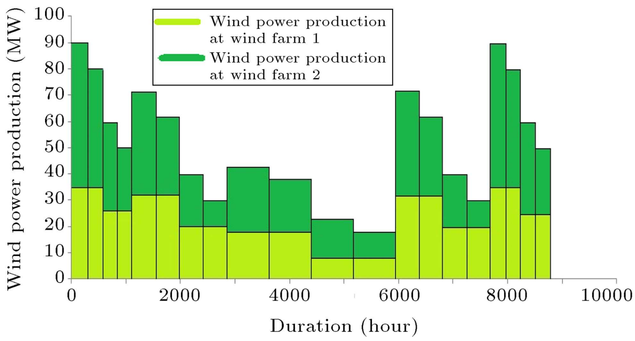

Figure 10. Summation of hourly wind power production of wind farms.

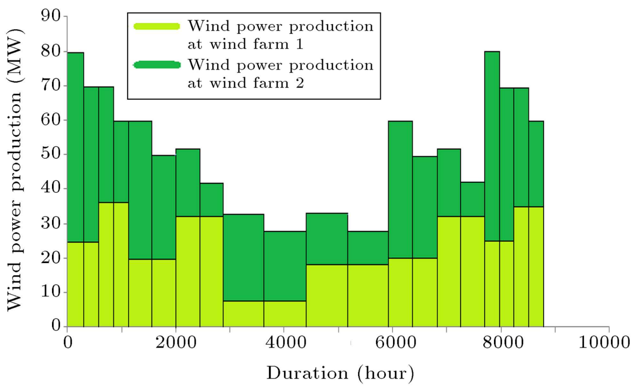

Figure 11. Summation of hourly wind power production of wind farms.

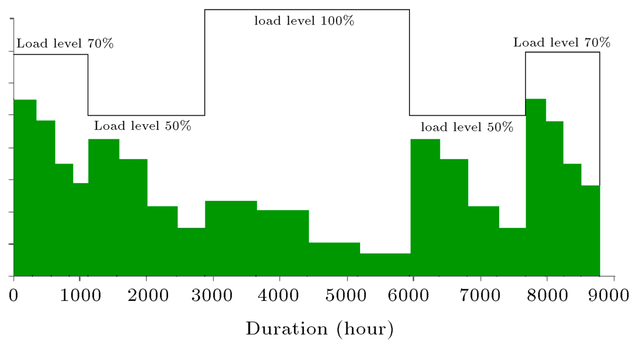

Figure 12. Distribution of WPDC during to LDC (scenario 1).

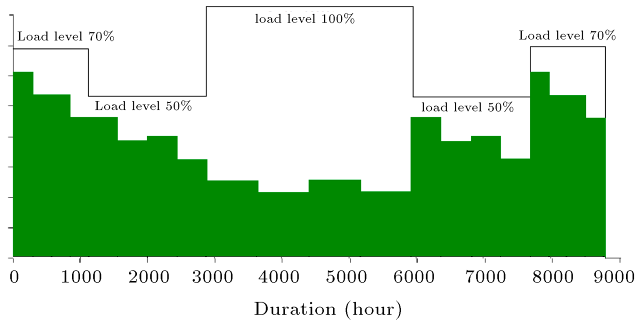

Figure 13. Distribution of WPDC during to LDC (scenario 2).

Table 3. Inductance of candidate lines before compensating.

Line number	Line inductance before compensating
36	0.35
39	0.45
40	0.2

are lines (27-28), (29-30), and (8-28), while the bus candidates for SVC are buses 8 and 21. The reactances of TCSCs are considered 0.2 to 0.7 of reactance of line candidates and the installed capacity of SVCs is assumed to be -20 to 30 MVar. The Inductances of candidate lines before compensating have been given in Table 3.

5.2. The considered cases

In this section, the proposed planning is applied to the test system. Two different cases have been analyzed in this article to show the effectiveness of the proposed method:

Case 1. No compensation is carried out (no FACTS devices);

Case 2. TCSCs and SVCs are installed in the system.

In both of the above cases, the two mentioned scenarios are simulated and the results are obtained. Then, the different aspects of the study in each of the cases are compared with each other. Finally, the system load ability in these cases will be examined by implementing various load factors and the operational condition of each case.

5.3. Numerical results

Tables 4, 5 and 6 provide social welfare, load shedding, and wind power spillage with and without the installation of FACTS devices in different load levels and operating conditions.

Because of the existence of congested lines during the peak load (load level 100%), all the wind power capacity of the wind farm 2 has been spilled. By compensating the mentioned lines and buses, wind

Table 4. Operating condition in various wind power generations for load level 100%.

Load level 100%												
Wind generation (MW)		Social welfare ($/hr)		Load shed (MW)		Spilled wind capacity (MW)		Line inductance after compensating by TCSC			Required SVC capacity (MVAR)	
Wind farm 1	Wind farm 2	w/o FACTS	With FACTS	w/o FACTS	With FACTS	w/o FACTS	With FACTS	Line 36	Line 39	Line 40	Bus 8	Bus 21
25	18	-42338.27	-58881.51	13.6	0	18	0	0.0063	0.2382	0.1463	30	20.9
25	8	-42338.27	-58805.35	13.6	0	8	0	0.0063	0.2382	0.1463	30	20.9
20	18	-48653.28	-58836.24	8.3	0	18	0	0.0048	0.2382	0.1449	30	20.83
20	8	-48653.28	-58759.74	8.3	0	8	0	0.0048	0.2382	0.1449	30	20.92
15	18	-44682.32	-58790.61	11.6	0	18	0	0.0058	0.2372	0.1404	30	20.8
15	8	-44682.32	-58713.87	11.6	0	8	0	0.0058	0.2372	0.1404	30	20.9
10	18	-40439.93	-58744.73	15.1	0	18	0	0.0118	0.2317	0.1472	30	20.87
10	8	-40439.93	-58667.71	15.1	0	8	0	0.0118	0.2317	0.1472	30	20.96

Table 5. Operating condition in various wind power generations for load level 70%.

Load level 70%												
Wind generation (MW)		Social welfare ($/hr)		Load shed (MW)		Spilled wind capacity (MW)		Line inductance after compensating by TCSC			Required SVC capacity (MVAR)	
Wind farm 1	Wind farm 2	w/o FACTS	With FACTS	w/o FACTS	With FACTS	w/o FACTS	With FACTS	Line 36	Line 39	Line 40	Bus 8	Bus 21
55	35	-41059.83	-41140.30	0	0	19.76	10.98	0.0135	0.0584	0.1	26.8	14.28
55	25	-41036.36	-41033.83	0	0	13.31	13.87	0.01	0.225	0.15	26.78	14.07
45	35	-41059.92	-41077.46	0	0	9.76	7.3	0.0094	0.0527	0.15	26.88	14.23
45	25	-41036.36	-41033.91	0	0	3.31	3.86	0.0128	0.2091	0.1419	26.8	14.07
35	35	-41019.90	-41044.33	0	0	6.52	2.93	0.0142	0.0524	0.1065	25.21	13.84
35	25	-40996.83	-40997.64	0	0	0	0	0.0114	0.2367	0.1356	27.28	13.64
25	35	-40951.62	-40973.12	0	0	6.52	3.47	0.0088	0.2242	0.152	27.07	13.28
25	25	-40928.65	-40929.47	0	0	0	0	0.01	0.2282	0.144	27.1	13.25

Table 6. Operating condition in various wind power generations for load level 50%.

Load level 50%												
Wind generation (MW)		Social welfare ($/hr)		Load shed (MW)		Spilled wind capacity (MW)		Line inductance after compensating by TCSC			Required SVC capacity (MVAR)	
Wind farm 1	Wind farm 2	w/o FACTS	With FACTS	w/o FACTS	With FACTS	w/o FACTS	With FACTS	Line 36	Line 39	Line 40	Bus 8	Bus 21
40	32	-29420.10	-29437.38	0	0	5.38	3.1	0.0106	0.2122	0.1375	16.84	5.49
40	20	-29379.78	-29378.18	0	0	0.22	0.55	0.0161	0.2107	0.1527	16.96	9.26
30	32	-29363.10	-29382.97	0	0	5.26	1.97	0.0157	0.0692	0.0891	17.46	9.67
30	20	-29322.51	-29322.81	0	0	0	0	0.0069	0.2357	0.1481	18.25	9.56
20	32	-29318.44	-29320.53	0	0	2.58	2.22	0.0065	0.0527	0.1128	16.93	9.65
20	20	-29259.26	-29260.53	0	0	0	0	0.0088	0.224	0.1429	18.7	9.16
10	32	-29238.65	-29260.01	0	0	5.26	1.89	0.0104	0.1717	0.0810	18.93	9.06
10	20	-29196.70	-29197.08	0	0	0	0	0.0125	0.2362	0.1356	19.12	8.97

farm 2 has become fully integrated into the power system. Social welfare in this load level had a significant improvement because of congestion relief, reduction in production of conventional generators, and, consequently, the decrease in their cost function. The increase in the penetration of wind energy into power system contributed to social welfare improvement. Moreover, it is observed that load shedding in this condition can be avoided (Table 4).

In 70% of the peak load, due to the extra wind power capacity, insufficient transmission line capacity and normal load level and various amounts of wind power have been spilled in both wind farms (Table 5). By using FACTS devices to compensate the system, the penetration of wind energy into the power system has been improved. At this load level in both conditions (i.e., with and without compensation), no load shedding happens due to low conventional marginal generation costs. Because of the little variation in the wind power revenue, the social welfare is improved, but less significant than when it is improved during load level 100%.

In Table 6, the operating conditions of 50% of peak load in various wind power generations are proposed. In these conditions, due to the low load level and more free capacity of the transmission lines, wind power could effectively be integrated into the power system, even without compensating. Therefore, at this load level, there is no significant difference whether we use compensating or not.

Figure 14 provides the annual wind power spillage percentage in different load levels with and without FACTS devices. It is observed that wind power spillage can be considerably reduced almost in all of the different load levels. During load level 100%, which is subject to voltage instability and high wind power spillage, the use of FACTS devices could completely resolve these problems. In this load level, because of the occupied lines, there is no chance for wind farm 2 to transfer its generated power; thus, practically, all of its capacity is spilled. Compensating the power system with FACTS overcomes congestion in transmission lines and thus, all of the generated power of wind farm 2 penetrates to the network.

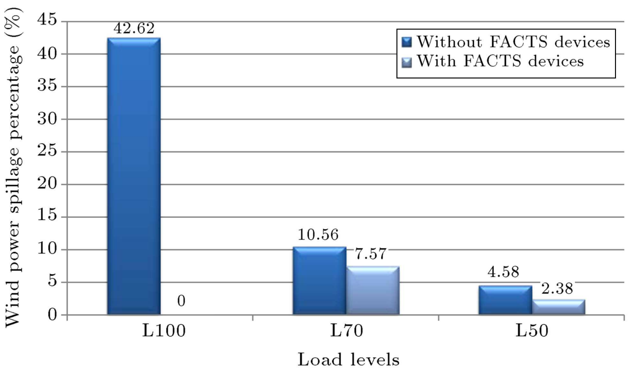

Figure 14. Wind power spillage in various load levels.

To evaluate static stability of the system, the load ability limit was analyzed. To this end, the simulations were carried out in different load factors. Three different operating conditions (without installation of FACTS and wind power production, without installation of FACTS and with wind power production, and with installation of FACTS and wind power production) were considered for evaluation of the proposed method with respect to power system stability. As could be observed in Figure 15, the proposed method has significantly improved the maximum load ability of the system. It may improve the flexibility of transmission lines by the use of TCSC and, consequently, the improvement in the voltage profiles due to the use of SVC results in enhancement of the load ability. Moreover, because of the increase in the penetration of wind energy into the power system, the system has the ability to supply more power and, consequently, the load ability of the system can improve.

In Figure 16, the total load and load shed of the system in different load factors are illustrated. For $\lambda \leq 0.51$, the system will continue working under normal conditions without any load shedding; but after that, the system will be vulnerable to voltage insta-

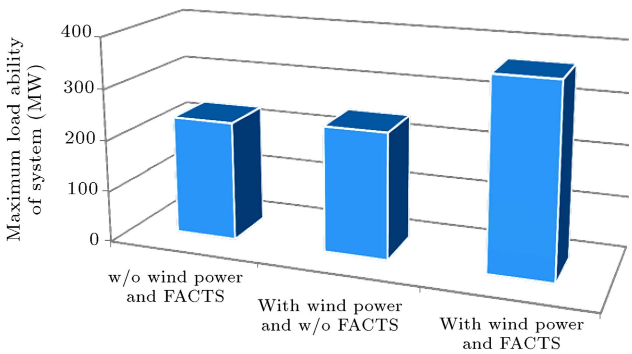

Figure 15. Maximum load ability of the system in three different states.

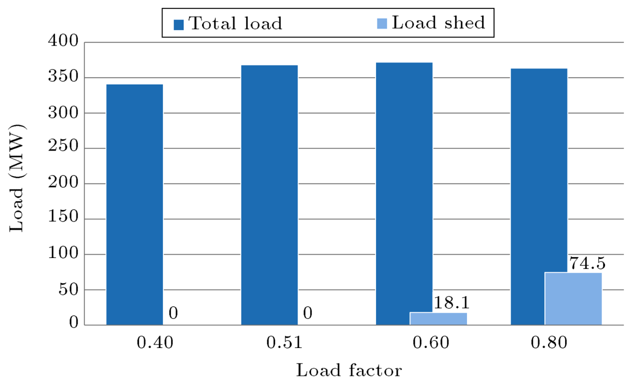

Figure 16. The total load of the system and load shed in different load factors in the presence of FACTS devices.

bility. In this condition, load shedding is inevitable for preserving the system stability until $\lambda = 0.8$. If $\lambda \geq 0.8$, the system will be unstable.

Social welfare in these conditions has been calculated as well. It is observed that despite the increase in the total load of the system, the use of the proposed method contributes to the social welfare improvement until $\lambda \approx 0.68$. For $\lambda \geq 0.68$, although the social welfare decreases, the static stability constraints are satisfied. As could be seen in Figure 17, the social welfare ascends until $\lambda = 0.68$; however, since the system is vulnerable to voltage instability, the social welfare comes down afterwards.

It is understood from these results that despite the increase in the system load and operating the power system in its security boundaries, the proposed method has improved the system ability to maintain its stability even to $\lambda = 0.8$. Social welfare has also a great improvement in normal condition as well as critical conditions. In critical conditions, despite the fact that operating power system is subject to voltage instability, the social welfare increases until $\lambda = 0.68$.

Figure 18 indicates a significant difference between the annual ESCs with and without installation of FACTS devices. Due to the use of the proposed method, a cost saving more than 45 million dollars is

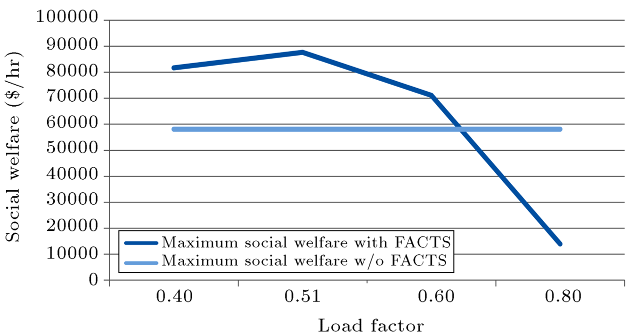

Figure 17. Maximum social welfare in different load factors with FACTS and maximum social welfare w/o FACTS.

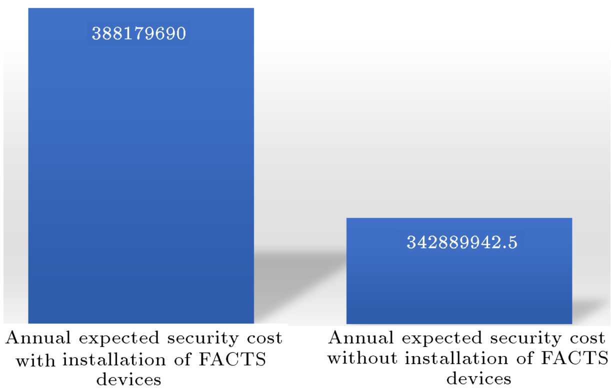

Figure 18. Annual ESC with and without installation of FACTS devices.

Table 7. The benefit obtained by the FACTS device installation.

Items	Amount ($)
Annual benefit in ESC due to implying the proposed method	45289747.5
Annual installation cost of FACTS devices	1182600
Annual cost saving	44107147.5

achieved (Table 7). This saving shows the economic effectiveness of the proposed method. This cost saving corresponds to the increase in wind power revenue and consumer benefit, and decrease in the generation cost of conventional generators. Based on Eqs. (5), (6), and simulation results, the annual installation cost of FACTS devices is calculated. Compared with the benefits obtained by the installation of FACTS, this installation cost is rather negligible.

6. Conclusion

In this article, the increase in the integration of wind farms into power systems and electricity market was successfully investigated. The presented planning problem was a multi-objective optimization problem. Our aim was to maximize social welfare and minimize investment and annual operation cost. At the same time, we managed to overcome line constraint by taking wind uncertainties into account. The uncertainties were taken into consideration by using two wind scenarios according to the maximum and minimum wind power production capacities of the wind farms. FACTS devices were utilized because of their ability to improve the power system stability. TCSC and SVC were selected as FACTS devices, and the ability of these devices in increasing the flexibility of the system improved. Furthermore, cost analyses were carried out to evaluate the benefits of the proposed method and the results showed its efficiency.

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