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Influence of DFIG Wind-Farm On the Optimal Allocation of VAR Devices

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Abstract. This paper develops an optimal planning tool for VAR devices in the presence of a doubly fed induction generator (DFIG) based wind farm. The probabilistic wind power output associated with the capability curve of DFIG wind generator has been incorporated in the proposed formulation in order to examine its effect on the new VAR devices investment cost and compare the results with the current practice of the regulated power factor range of 0.95 leading and 0.95 lagging. The proposed method is stated as an optimization problem so that the objective function is to simultaneously minimize the sum of the annual investment cost of the new VAR devices as well as the annual expected energy loss cost. The objective function is achieved while simultaneously satisfying the investment constraints of the new VAR devices and several operating constraints including the effect of the wind park active power output and its associated VAR capability limits as well as the voltage security limits to enhance power system voltage stability. .

***Keywords*:** DFIG, Optimal VAR Devices, SVCs, Capability Diagram

1. Introduction

Now days, in order to meet the energy requirements, wind power is progressively developed and is considered as a viable energy source that reduces the economical and environmental problems associated with the conventional energy resources. The variable-speed wind turbine equipped with doubly fed induction generators (DFIG) is currently the most common wind turbine technology installed in system due to its superior control capabilities. It has the ability to rapidly operate at the optimal point of the wind turbine and continuously control the reactive power through the integration of power- electronic converters. Recently, there is strong inclination towards installing more DFIG units resulting in increases in the wind power penetration level. Therefore, the investigation of the potential impacts of high wind penetration level on power system performance has become an active research area in recent years [1-2]. Precise modeling of DFIG units has been the subject of numerous studies in order to be accurately included in both static and dynamic analysis of power systems. The detailed mathematical static model representing DFIG capability curve (PQ diagram) similar to the one typically used for the synchronous generator in conventional power plants is developed in [3]. The interconnection requirements in many countries obligate wind farms to maintain power factor within the range of 0.95 leading to 0.95 lagging, thereby restricting the full utilization of the reactive capability of the DFIG units. This situation motivates several researchers to explore the effect of fully utilizing the capability curve of DFIG in the power system enhancement. The operation of DFIG at much lower power factor without incurring additional converter costs has been validated in [4]. It has been also demonstrated that committing the full reactive capability of a DFIG park can produce a significant reduction in system losses, improve post-fault voltage profiles and may prevent voltage collapse. A joint algorithm to simultaneously obtain optimal reactive power output of DFIG farm and the optimal network configuration considering DFIG reactive capability limits has been proposed in [5]. It has been concluded that wind farm made up of DFIG can constitute an important continuous reactive power source to support system voltage control, which in turn reduces power losses and improves voltage profile. The results of the mentioned works imply that the excessive underutilized reactive capacity of DFIG is crucial to enhancing system performance. The full utilization of VAR capacity of DFIG can be extended to the long-term VAR-planning problem since it mainly relies on the capacity of the available VAR sources in the system. Therefore, it is necessarily required to appropriately incorporate DFIG capability curve into the conventional VAR planning problem and examine its effect on the investment cost of new reactive power devices which is the interest of this paper .

The present paper aims to develop a new long term reactive power planning tool that considers the reactive power capability of a DFIG wind farm. The variability of wind power output of DFIG is incorporated in the proposed formulation by taking into account the uncertain nature of the wind speed. The proposed method is stated as an optimization problem so that the objective function is to simultaneously minimize the sum of the investment cost of the new VAR devices as well as the expected operating costs of the simulated states that include probabilistic output of DFIG wind farm. The Weibull distribution of the wind speed is used to represent the wind park output (active and reactive power) as a set of discrete values each of which has its own probability. This treatment enables easily incorporation of the expected active power and reactive power limits of DFIG-based wind farm into the proposed formulation. The overall problem is formulated as large-scale mixed integer nonlinear programming with a non-differentiable objective function and huge numbers of constraints associated with the simulated states. Since the presented problem is hard to be solved by the conventional method, particle swarm optimization (PSO) is employed as an efficient solution method for solving the combinatorial optimization problems as the problem at hand.

2. DFIG Wind Turbine Model

The variable speed wind turbines based on the Doubly-Fed Induction Generator are connected to the grid using power-electronic converter technology. The power electronic converters enable DFIG turbines to control their own reactive power, so as to operate at a specified power factor or to control the terminal voltage. Fig. 1 depicts the T equivalent model that characterizes the steady-state operation of DFIG turbine. The fundamental steady state equations describing the relation between rotor and stator voltages and currents are given as:

$$V_s = R_s I_s + jX_1 I_s + jX_m (I_s + I_r) \tag{1}$$

$$\frac{V_r}{S} = \frac{R_r}{S} I_r + jX_2 I_r + jX_m (I_s + I_r) \tag{2}$$

where V_s is the stator voltage, Vr is the rotor voltage, I_s is the stator current, I_r is the rotor current, R_s is the stator resistance, R_r is the rotor resistance, X_s is the stator reactance, X_r is the rotor reactance, X_m is the mutual reactance, and S is the slip.

The net active power Pnet delivered to the grid is given by the sum of stator and rotor active power and can be approximately expressed in terms of the slip of the machine and stator active power Ps. The grid side converter is normally controlled to operate at unity power factor and hence the net reactive power (Q_{net}) delivered to the grid is equal to stator reactive power Q_s. Then, the net power delivered by the generator to the grid can be expressed as follows:

$$P_{net} = (1-S) P_s \tag{3}$$

$$Q_{net} = Q_s \tag{4}$$

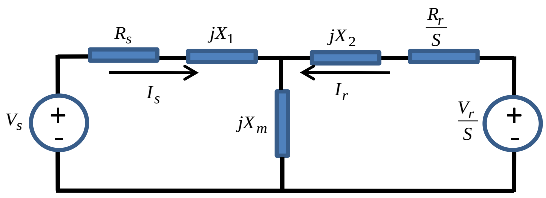

Fig. (1). DFIG Equivalent Circuit

A. Capability Curve of DFIG

The above fundamental equations are used to derive a set of steady-state equations that define the PQ capability curve of DFIG turbine, which is similar to the capability curve of the conventional synchronous generator [3]. The reactive power output of the turbine relies mainly on the active power output, rotor slip and the boundary limits caused by the stator and rotor maximum allowable currents as well as the maximum rotor voltage. Fig. 2 illustrates the PQ diagram of DFIG machine that can be obtained based on the technique presented in [3]. The total active and reactive power for entire slip range (-0.25 to 0.25) as well as power factor range (0.95 leading to 0.95 lagging) are displayed in figure 2. The figure indicates that there is an additional reactive power of the capability curve over the regulated power factor especially when the wind turbine operates below its rated power output. The operation of DFIG turbine over the regulated power factor at no extra converter costs has been validated in [4]. The excessive VAR output of the capability curve can significantly contribute to enhance the power system performance. Therefore, the interest of this paper is to fully utilize excessive VAR capacity of DFIG in the long-term VAR-planning problem since it mainly relies on the capacity of the already available VAR sources in the system .

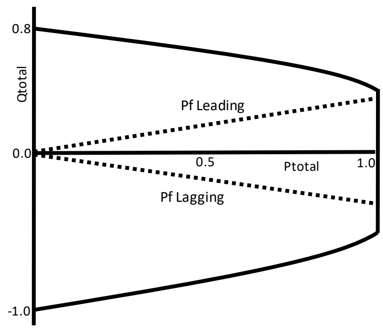

Fig. (2). Capability Curve of DFIG

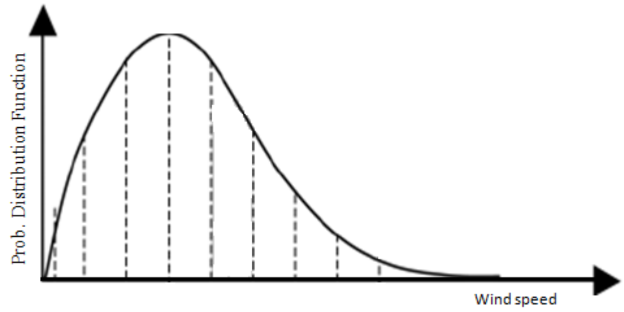

Fig. (3). Weibull Distribution

B. Probabilistic Model of Wind Power Plant

The wind power is a function of the wind speed and it can be generally forecasted through the forecasted wind speed. Normally, the wind speed in a specific site has the same profile on annual basis, where its variation can be best described by Weibull distribution shown in figure 3. The probability density function (PDF) of Weibull distribution is given as :

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^{k}\right) \tag{5}$$

where v is the wind speed, A is the scale parameter and k is the shape parameter. The PDF shown in figure 3 can be divided into number of equal segments each of which has a mean speed value. Then, the probability of specific wind speed v which is the mean value of v_i and v_j might be written as:

$$\Pr ob(v = v_m) = \int_{v_i}^{v_j} f(v) = \exp\left(-\left(\frac{v_i}{A}\right)^{k}\right) - \exp\left(-\left(\frac{v_j}{A}\right)^{k}\right) \tag{6}$$

The wind farm power output is a function of wind speed where the mean speed can be transformed into real power output using manufacturers' curves or can be used in the linear, parabolic or cubic function that approximately describes the relationship of the wind power output and wind speed [6]. Note that if the wind speed under the cut-in and over the cut-out speeds, the wind farm output is zero while the output power is constant at its rated value if the wind speed is within the range of rated to cut-out speeds. It is therefore possible to approximately represent the probabilistic distribution of the wind farm power output as a set of discrete values with the corresponding probabilities. The VAR limits associated with each discrete value is then determined using the capability curve illustrated in figure 2 as formulated in [3].

3. Problem Formulation

This section is devoted to reformulate the VAR planning problem so as to take into account the capability curve of DFIG wind farm. In order to consider the variability of wind power output, the above mentioned technique is used to generate a set of discrete values of active power and VAR limits with their associated probabilities. The obtained discrete values with the corresponding probabilities are incorporated into the conventional long-term VAR planning problem, and consequently, enabling the assessment of investment cost of new VAR sources in the presence of extended capability curve of DFIG. The problem is stated as an optimization problem where its objective function and associated constraints are defined below.

A. Objective Function

The proposed objective function is assumed to minimize the sum of installation cost of new VAR devices and the expected operating costs for the individual states representing the system conditions under each obtained discrete value. In this paper, the static VAR compensators are selected as new VAR expansion devices, while the operating cost is chosen to be the cost of energy losses of the network. According to the available practical data in [7], the investment cost of new SVCs is obtained using (8) and (9). A more detailed explanation of (8) and (9) is given in [8]. The expected annual cost in this case might be stated as follows:

$$minimize: F_{total} = F_{It} + \sum_{t=1}^{Ns} P_{rob}{}^{(t)} F^{(t)} \tag{7}$$

$$F_{It} = \frac{ir(1+ir)^{Dy}}{(1+ir)^{Dy}-1} F_{It0} \tag{8}$$

$$F_{It0} = \sum_{i=\Omega} (\mu_{isvc} c_{isvc}) d_{isvc} \tag{9}$$

Where F_{It0} is investment cost of new SVC, d_{isvc} is integer value 0 or 1, which indicates whether an SVC is installed in site *i* or not, Ω is set of all candidate buses, μ_{isvc} is the investment cost for SVC in $/KVAR, c_{isvc} is the size of installed SVC in MVAR, F_{It} is annual value of the investment cost, ir and Dy in (6) are the interest rate and life period of SVC, respectively. *F(t)* is annual energy loss cost associated with system state t. *Prob(t)* is the probability of system state t computed using (6). Ns is the number of the simulated system states.

B. Investment and Operating Constraints

The above objective is achieved while simultaneously satisfying the investment constraints of the new VAR devices and several operating constraints representing power flow equations and operational limits of the state and control variables as well as the voltage security limits to enhance power system voltage stability. The investment constraints stand for the additional VAR amount c_{isvc} are represented as follows:

$$0 \le c_{isvc} \le c_{isvc-\max} \quad \text{for i} \in \Omega, \tag{10}$$

The operating constraints include a set of constraints corresponding to the system states under each discrete value obtained as described in section II. For each individual state, in order to maintain the voltage security margin, two sets of constraints are defined, the nominal load operating point constraints (11) and point of collapse constraints (12). The details of equations (11) and (12) are presented in the authors' previous work [9].

$$\left.\begin{array}{l} y_b^t \text{ - } f(x_b^t, u_b^t, c_{ib}^t) = 0 \\ x_{\min} \le x_b^t \le x_{\max},\ u_{\min} \le u_b^t \le u_{\max}, \\ 0 \le c_{ib}^t \le c_{isvc} \end{array}\right\}, (\text{t=1,2,...,Ns}) \tag{11}$$

$$\left.\begin{array}{l} y_b^t + (\lambda_c^t - 1) y_d \text{ - } f(x_c^t, u_c^{(t}, c_{ic}^t) = 0 \\ w(x_c^t, u_c^t, \lambda_c^t, c_{ic}^t) f_x(x_c^t, u_c^t, \lambda_c^t, c_{ic}^t) = 0, \quad \|w\| \ne 0 \\ \text{u}_{\min} \le u_c^t \le u_{\max}, \quad \lambda_c^t \le \lambda_{\min}, \quad 0 \le c_{ic}^t \le c_{isvc}, \end{array}\right\}, (\text{t=1,2,...,Ns}) \tag{12}$$

where subscript b indicates the nominal load operating point. T=(1,2…,Ns) refers to the simulated cases. y_b is the active and reactive power mismatch vector *"including the wind farms outputs"* at nominal load operating point. f is power flow equations at nominal load. Subscript c indicates the collapse point. w is left eigenvector " row vector". f_x is power flow Jacobian " singular at nose point". y_d is load direction vector. λ is the load parameter value. x is the state variables vector. u is control variables vector "existing VAR control devices". c_{ic} is control vector of new SVCs.

Note that the impact of the wind farm outputs (active and reactive power) is considered in the load flow constraints (11-12) by incorporating their values into the active and reactive power mismatch vector y_b^t. Note also that the existing VAR devices control vector u^t includes VAR limits of the wind farm that have been obtained using VAR capability curve.

4. Solution Algorithm

The problem formulation described in section III is classified as a large scale mixed integer non-linear programming problem. The advanced heuristic methods are considered promising techniques in solving this type of problem. Consequently, an optimization technique based on a hybrid PSO and successive linear programming (PSO/SLP) for finding global optimal solution of (7-12) is presented in this section. The computational procedures of the developed method are summarized in Fig.4. The algorithm starts from a random initial swarm, where its particles are indicated in Fig. 4 by prc.1, prc.2.,…., prc.m,. Each particle in the swarm represents a candidate solution which is the VAR sizes of new SVCs. For instant, assume particle 1(prc.1) represents a candidate sizes of new SVCs, where its annual investment F_{It} can be directly computed using (7-8). This candidate is used as a common solution for all simulated states describing the system conditions under the obtained discrete values of wind farm. The SLP is employed to separately solve the optimization problem for each individual state where the associated objective function for the state t is ($P_{rop}{}^{(t)}F^{(t)}$) and its corresponding operating constraints are (11) and (12). Based on the optimization results, the fitness of prc.1 is evaluated in terms of F_{total} . The same computational procedures will be repeated for each particle in the swarm. Accordingly, the best previous position for each particle and best particle among all the particles are stored in a solution set. Then, the new velocity and position for each particle are updated producing next iteration. These procedures are repeated till a termination criterion is satisfied [10].

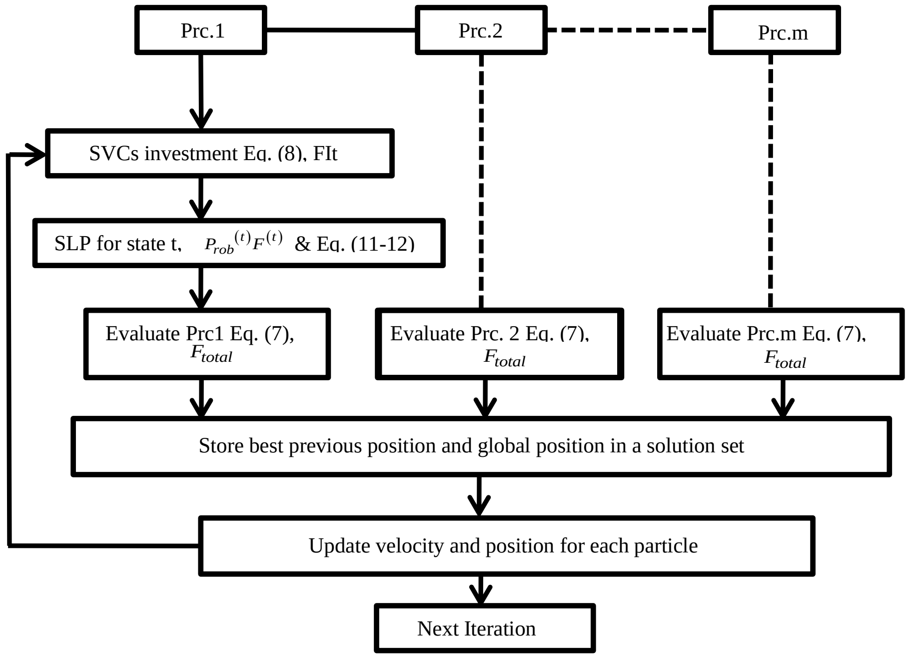

Fig. (4). A hybrid PSO/SLP solution method

5. Simulation Results

The proposed method has been applied on IEEE-14 bus system. To assess the efficiency of proposed approach, the following two cases have been analyzed. In case I, the reactive power output of DFIG wind turbine is assumed to be regulated within the power factor range of 0.95 leading to 0.95 lagging, while in case II, the VAR limits of DFIG capability curve are fully utilized. Based on the modal analysis technique, the weakest three buses which are buses 9, 10 and 14 have been set as candidate buses for installing new SVCs. Parameters used for the examinations are given as follows: v_{min}=0.9 pu, v_{max}=1.1 pu, *ir=0.04, Dy=10 years,* desired load margin=0.2, $c_{isvc-\max}$=0.3 pu, *Ns*=12. The wind farm which represents an aggregate multiple DFIG turbines is assumed located at bus 5. The rated power of the wind park is chosen 60 MW where the technical parameters of the 1.5 MW DFIG wind generator are given in [4].

Table (1) shows the discrete values (simulated scenarios) of the wind farm output in terms of the active power and reactive power that have been determined according to the respective wind speed. The VAR limits indicated in the table stand for both of the regulated power factor range and the limits of the capability curve demonstrated in Fig. 2. The probability of each discrete value is also provided in the table.

In order to assess the developed method, the base case in the two simulated cases presented below is defined first by stressing the system to 150 % of the original load. Then, the most severe contingency has been adopted for the examinations, where the load margin value and bus voltage magnitudes violate pre-specified limits.

Table (1). Active and reactive power output of DFIG wind turbine

State Number	Active Power Output (pu)	Regulated Power Factor Limits (Q_{max} , Q_{min}) (pu)	Capability Curve Limits (Q_{max} ,Q_{min}) (pu)	Prob. of State
1	0.010	(0.0,0.0)	(0.79,-.995)	0.050
2	0.017	(0.006,-0.006)	(0.78,-0.99)	0.083
3	0.045	(0.015,-0.015)	(0.77,-0.97)	0.114
4	0.087	(0.029,-0.029)	(0.76,-0.95)	0.138
5	0.146	(0.048,-0.048)	(0.75,-0.93)	0.146
6	0.224	(0.074,-0.074)	(0.73,-0.91)	0.137
7	0.324	(0.107,-0.107)	(0.69,-0.88)	0.114
8	0.448	(0.147,-0.147)	(0.65,-0.84)	0.083
9	0.601	(0.198,-0.198)	(0.58,-0.79)	0.053
10	0.784	(0.258,-0.258)	(0.48,-0.75)	0.029
11	0.977	(0.321,-0.321)	(0.40,-0.67)	0.015
12	1	(0.329,-0.329)	(0.37,-0.69)	0.0140

Table (2). SVCs sizes and annual costs with regulated Pf.case

SVCs Bus Number	*9*	10	14
SVCs VAR Size (pu)	0.15	0.27	0.27
Expected Energy Loss Cost ($)	3.8894e+003		
Investment Cost (FIt), ($)	1.0219e+006		
Total Cost (Ftotal), ($)	1.0258e+006		

Table (3). Bus voltages and load margins with regulated Pf case

State Number	Just After Contingency		After SVCs Expansion	
	v_{min} (pu)	Load margin	v_{min} (pu)	Load margin
1	0.72	0.043	0.94	0.20
2	0.73	0.045	0.95	0.20
3	0.74	0.049	0.95	0.20
4	0.74	0.055	0.95	0.20
5	0.75	0.063	0.96	0.20
6	0.77	0.075	0.96	0.20
7	0.78	0.088	0.96	0.20
8	0.80	0.108	0.96	0.20
9	0.81	0.127	0.97	0.21
10	0.83	0.146	0.97	0.21
11	0.85	0.175	0.97	0.21
12	0.85	0.179	0.97	0.21

1) *Case I: SVCs Expansion With the Regulated Power Factor of DFIG Turbine*

In this case, the problem has been solved with the active power outputs shown in Table (1) and their associated VAR limits which are relevant to the regulated range of the power factor. The results of this examination are listed in Table (2) where the optimal SVC allocations are 0.15, 0.27, and 0.27 pu at buses 9, 10, and 14, respectively. The results indicated that all candidate buses are adopted for installing new SVC in order to maintain the desired limits of the load margins and voltage magnitudes for all simulated cases. The table demonstrates also the annual expected energy loss cost, investment cost and the total cost required to achieve the desired target when the DFIG turbine is restricted to operate within the regulated power factor range. Table (3) lists the minimum bus voltage magnitudes and load margins for the simulated cases, showing the effect of the SVCs installation for case I compared with just after contingency state without SVCs installation. It is observed that, just after contingency, voltage magnitudes are violated and load margins are too small. As shown in the table, the violations of the desired limits are relived after the SVCs installation.

Table (4). SVCs sizes and annual costs with capability curve case

SVCs Bus Number	*9*	10	14
SVCs VAR Size (pu)	0.17	0.0	0.0
Expected Energy Loss Cost ($)	4.5998e+003		
Investment Cost (FIt), ($)	2.5629e+005		
Total Cost (Ftotal), ($)	2.6089e+005		

Table (5). Bus voltages and load margins with capability curve case

State Number	Just After Contingency		After SVCs Expansion	
	v_{min} (pu)	Load margin	v_{min} (pu)	Load margin
1	0.84	0.142	0.93	0.20
2	0.84	0.145	0.93	0.20
3	0.84	0.148	0.93	0.20
4	0.84	0.151	0.94	0.20
5	0.84	0.155	0.94	0.20
6	0.85	0.160	0.94	0.20
7	0.85	0.165	0.94	0.20
8	0.85	0.173	0.95	0.20
9	0.86	0.178	0.95	0.21
10	0.86	0.182	0.95	0.21
11	0.86	0.188	0.95	0.21
12	0.86	0.189	0.95	0.21

2) Case II: SVCs Expansion Considering Capability Curve of DFIG Turbine

In this case, the reactive capability curve of DFIG turbine is fully utilized in order to examine its effect on the investment cost of new SVCs. The discrete active power values shown in Table (1) and their associated VAR limits computed according to the capability curve are employed in this analysis. The results of this examination are listed in Table (4) where the optimal SVC allocations are 0.17, 0.0, and 0.0 pu at bus 9, 10, and 14 respectively. The results show that only one SVC at bus 9 is found sufficient to maintain the desired limits for all simulated cases. The annual expected operating cost, investment cost and the total cost required to achieve the desired target are also presented in the table. It is clear that the investment cost has been significantly decreased compared to case I and, in turn, reduces the total cost. This clarifies the positive effect of utilizing the excessive VAR capacity of DFIG as it increases the amount of the available VAR sources in the system. The minimum bus voltage magnitudes and load margins for all simulated cases in this analysis are given in Table (5). As shown in the table, just after contingency, voltage magnitudes and load margins are violated while these violations are relived after the SVCs installation. Note that, just after contingency state, the minimum bus voltages and load margins have been increased in case II compared to case I as a result of increasing the VAR limits of DFIG turbine. The preceding results validate the importance of adequate incorporation of DFIG capability curve into the conventional VAR planning problem for achieving a remarkable saving in the total cost.

6. Conclusions

This paper deals with the effect of the extended reactive capability curve of DFIG wind generator on the long-term reactive power planning problem taking into account the voltage security. The capability curve of DFIG wind generator is approximately modeled as a set of discrete values of active power and VAR limits with their associated probabilities reflecting the uncertain nature of the wind speed. Since the problem is stated as a large scale mixed integer non-linear programming problem, a PSO/SLP method is employed to solve the overall problem. The proposed approach has been successfully examined on IEEE 14 bus test system. The obtained results show that the inclusion of extended DFIG capability curve into the conventional VAR planning problem maintain the desired security limits during the simulated states while a remarkable saving in the investment cost has been achieved compared with the current practice of the regulated power factor range of 0.95 leading and 0.95 lagging.

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تأثير مزارع رياح المولدات الحثية ثنائي التغذية على المكان الأفضل لأجهزة القدرة غير الفاعلة

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ملخص البحث. يقدم البحث أداة تخطيط مثالي لأماكن القدرة غير الفاعلة في وجود مزارع رياح المولدات الحثية ثنائية التغذية، ولقد تم إعتبار احتمالات القدرة الخارجة والمرتبطة بمنحنيات الاستطاعة للمولد ثنائي التغذية في الصياغة المقترحة، وذلك لفحص تأثير ذلك على الاستثمار في الأجهزة الحديثة للقدرة غير الفاعلة، ومقارنتها بنتائج الممارسات الحالية لتنظيم معامل القدرة في مدى بين ٠,٩٥ متقدم و٠,٩٥ متأخر. وتصاغ المسألة تحت الدراسة على أنها مسألة أداء أفضل، بحيث تكون دالتها المستهدفة هي التكلفة الناتجة من التكلفة السنوية لأجهزة القدرة غير الفاعلة ووفر الفقد السنوي للطاقة، آخذين في الاعتبار قيود الاستثمار وحدود أمان الجهد بغرض تحسين استقرار جهد نظام القدرة الكهربائية.