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Optimal Reactive Power Control in Transmission Network With a Large Wind Farm Connection

B.P. Numbi, D.W. Juma, .J.L. Munda, A.A. Jimoh
Tshwane University of Technology, Department of Electrical Engineering, Pretoria 0001, South Africa
E-mail: numbibp@tut.ac.za, jumadw@tut.ac.za, mundajl@tut.ac.za, jimohaa@tut.ac.za

Abstract— **In a weak network where the reactive power capability is not able to satisfy the demand of wind farm based on squirrel-cage induction generator (SCIG), flexible AC transmission system such as static VAR compensator (SVC) is used. Traditionally, the SVC device and other network reactive power facilities are used in optimal way by the network operator, for optimal voltage profile and loss minimization, during different steady-state operations caused by wind resource changes. In this paper, the SVC reactive power reserve (SVC-RPR) is added to the problem as a third objective function to be maximized with the purpose of further compensation usage during dynamic operation. Particle swarm optimization (PSO) is used to optimize the search space of this multi-objective problem. The reactive power optimization scheme is tested in a MATLAB/R2010a based simulation model of Wale & Hale 6-bus system with wind farm integration. It is has been found that the conflict between the three objective functions causes the difficulty of achieving a sufficient SVC-RPR during high wind farm power generation, unless the SVC rating is designed in such away to be higher than the reactive power required by the total number of SCIG at full load.**

Keywords-Optimal reactive power control; wind farm; multi-objective, SVC-RPR, SCIG; PSO.

I. INTRODUCTION

Wind energy conversion has been revealed as the fastest growth power generation in the world. According to [1], the worldwide installed capacity reached 59.091GW in 2005, 74.052GW in 2006, 93.835GW in 2007, 120.798GW in 2008, 158.738GW in 2009 and 194.4GW in 2010. This spectacular growth is due to the fact that the generation costs have fallen dramatically over the last 15 years, moving closer to the cost of conventional energy sources [1]. Power rating, efficiency and reliability of wind turbines have been improved. However, the big amount of reactive power demand of a large wind farm based on squirrel-cage induction generator (SCIG) may not be satisfied by the grid. Therefore, if this issue is not well planned, the connection of a large wind farm would cause voltage instability as well as increase of energy loss in the power system [2]. The solution would be to supply locally, as close as possible, the reactive power to the wind farm.

In an effort to solve this problem, flexible AC transmission system (FACTS) devices such as static VAR compensators (SVCs) are commonly used to compensate the reactive power of wind farm. Therefore, during the steady-state, the SVC and other reactive power controller such as on-load tap changer (OLTC) transformers, generator excitation, switchable shunt capacitors, switchable inductors, etc. should operate in optimal way in such a way to improve the voltage profile by minimizing the total active power losses. During the last few years, many techniques have been used to solve the optimization of reactive power control in power system operation.

The most traditional techniques used for VAR optimization are as follows: nonlinear programming, success linear programming, mixed integer programming, Newton and quadratic techniques [3, 4]. The high nonlinearity characteristic of reactive power control causes the search space of this problem to have several local minima. Therefore, the traditional techniques which are based on derivative method and good starting point may not be able to explore efficiently this search space in order to get the global minima. For this reason, recently, new methods based on artificial intelligence (AI) or Evolutionary algorithms (EAs) have been used. These techniques include artificial neural network (ANN), tabu search (TS), simulated annealing (SA), expert system (ES), genetic algorithms (GAs), differential evolution (DE), evolutionary programming (EP), particle swarm optimization (PSO), etc[3, 4]. However, PSO was revealed to have many advantages over other similar AI methods [4, 5] and is even considered to be the best [6].

Until now, the two objective functions that have been commonly considered to be minimized in a grid with wind farm based on SCIG, are the active power losses and voltage deviations [2, 7, 8]. Although, the optimization of reactive power control has been shown to be mainly intended for steady-state purpose, null or poor reserve in SVC reactive power may lead to a poor oscillation damping of voltage profiles under post-fault and wind speed change conditions as well. With this in mind, in this paper, a third objective function which is the SVC-RPR is also taken into account while being maximized during the normal operation of the wind farm. It is assumed in this paper, that all possible connection points of the wind farm into the grid have the same wind resource potential. Hence, before connecting the wind farm, Newton-Raphson (NR) algorithm is used to assess the possible appropriate location in terms of lower active power losses and/or voltage deviations. After appropriate location has been selected, PSO is used to explore the search space of this nonlinear problem in order to get the optimal control variables for minimal power losses, voltage deviations and maximal SVC reactive power reserve. Exterior quadratic penalty terms are used to incorporate all equality and inequality constraints into the three objective functions. After running PSO algorithm to solve the problem, the optimal control variables obtained are used by NR algorithm in order to adjust all the state variables of the network system. A lumped wind farm connected into Wale & Hale 6-bus system is used to validate the proposed method.

II. WIND GENERATOR MODEL FOR POWER FLOW CALCULATION

A. Introduction

The squirrel-cage induction generator (SCIG) is commonly used in fixed-speed wind farms because of its low cost, long life, robustness, simple structure and ease to be integrated into the electrical grid [7, 9].

The conventional PQ bus model being the most used, the active and reactive powers of SCIG should have constant values [10]. To get the active power constant, the daily active power output curve is discretized as a step-like function by time [2, 8]. The reactive power consumed by the wind farm is therefore expressed as a function of active power output and terminal voltage for power flow calculation [2, 7].

B. Squirrel-cage induction generator model

The figure 1 shows the steady-state, simplified equivalent circuit of the SCIG with all quantities in this circuit referred to the stator. X_S is the stator leakage reactance, X_r is the rotor leakage reactance, R_r is the rotor resistance, X_m is the magnetizing reactance and s is the slip. The terminal voltage, V, wind turbine active power output, P_{WT} and reactive power consumed, Q_{WT} are the per-phase RMS quantities. In this circuit, the stator resistance is ignored.

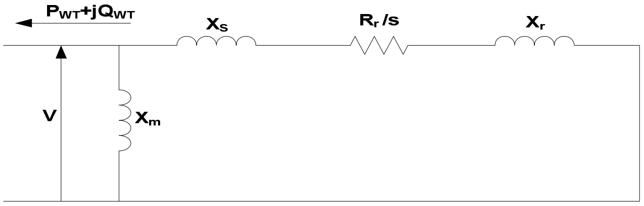

Figure 1. The simplified equivalent circuit of SCIG

From figure 1, the active power injected by the wind turbine based on SCIG, to the electrical grid is expressed by equation (1).

$$P_{WT} = \frac{-V^2 \frac{R_r}{s}}{\left(\frac{R_r}{s}\right)^2 + X^2} \tag{1}$$

Where $X = X_s + X_r$

The equation (1) can be rearranged as a second order equation where s is the variable. The acceptable solution is:

$$s = \frac{-V^2 R_r + \sqrt{V^4 R_r^2 - 4P_{WT}^2 X^2 R_r^2}}{2P_{WT} X^2} \tag{2}$$

From the same figure 1, it can be seen that the impedances jX_m and $\frac{R_r}{s} + jX$ are in parallel. Therefore, the equivalent impedance can be expressed as (3):

$$Z_{eq} = \frac{-X_m X + jX_m \frac{R_r}{s}}{\frac{R_r}{s} + j(X + X_m)} \tag{3}$$

Taking (3), after multiplying its denominator and numerator by its denominator conjugate, the tangent of the power factor angle of the SCIG is deduced and given, after mathematical simplification, as (4):

$$\tan\varphi = \frac{s^2 X(X + X_m) + R_r^2}{sX_m R_r} \tag{4}$$

The reactive power absorbed by the wind turbine will be expressed as (5):

$$Q_{WT} = P_{WT}\tan\varphi = \frac{s^2 X(X + X_m) + R_r^2}{sX_m R_r} P_{WT} \tag{5}$$

Substituting (2) in (5) yields the reactive power which is function of the terminal voltage and active power output of the wind power. This is given by equation (6).

$$Q_{WT} = -\frac{\sqrt{R_r^2 V^4 - 4P_{WT}^2 R_r^2 X^2} + R_r V^2}{2R_r X_m} - \frac{(X + X_m)\left(\sqrt{R_r^2 V^4 - 4P_{WT}^2 R_r^2 X^2} + R_r^2 V^2\right)\left(\sqrt{R_r^2 V^4 - 4P_{WT}^2 R_r^2 X^2} - R_r^2 V^2\right)^2}{8P_{WT}^2 X^3 R_r^3 X_m} \tag{6}$$

The equation (6) can be approximated by a second order equation by means of McLaurin polynomial. In this polynomial, the terminal voltage V is assumed to be constant and the variable is the wind farm active power output P_{WT}. Hence, the constant term in the approximated equation will express the no-load reactive power and the remaining term will express the load dependent reactive power.

In this work, the small variation of V around its rated value is ignored during the wind speed change. Therefore, the reactive power absorbed by the wind turbine is calculated at rated SCIG voltage. With this simplification, the error is not significant [10].

III. MATHEMATICAL MODEL OF THE MULTI-OBJECTIVE WIND FARMS WITH GRID CONNECTION

A. Minimize the total active power losses

The first objective function in this multi-objective function is the total power losses to be minimized, given as (7):

$$\min_1 P_{loss} = \sum_{L=1}^{NL} g_L \left(V_i^2 + V_j^2 - 2V_i V_j Cos\delta_{ij}\right) \tag{7}$$

B. Minimize the total voltage deviations

With the purpose of getting a higher-quality load voltage profiles, the average of load voltage deviations from a nominal voltage (1 p.u. in this paper) is minimized and forms the second objective function as follows:

$$\min_2 \varepsilon_V = \sum_{i=1}^{ND} \frac{\max |V_{Di} - V_{i,nom}|}{ND} \tag{8}$$

C. Maximize the SVC reactive power reserve

This third objective function is formulated in quadratic form as given below:

$$MaxR_{QSVC} = \left(Q_{SVCi}^{\max} - Q_{SVCi}\right)^2 \tag{9}$$

This can be rewritten for minimization formulation as:

$$Min_3 R_{QSVC} = -\left(Q_{SVCi}^{\max} - Q_{SVCi}\right)^2 \tag{10}$$

D. Equality constraints

The equality constraints in optimal reactive power problem are the power flow equations for balancing the power within the network. These constraints are given as:

$$\begin{cases} P_{Gi,WTi} - P_{Di} - V_i \sum_{j=1}^{NB} V_j |Y_{ij}| Cos\left(\theta_{ij} - \delta_i + \delta_j\right) = \Delta P = 0 \\ Q_{Gi,WTi} - Q_{Di} + V_i \sum_{j=1}^{NB} V_j |Y_{ij}| Sin\left(\theta_{ij} - \delta_i + \delta_j\right) = \Delta Q = 0 \end{cases} \tag{11}$$

E. Inequality constraints (limits)

These are state and control variables of power system hardware (equipment) and operating constraints. The wind turbine active power output and reactive power absorbed should also be kept within their limits during the wind resource variation. These are fixed variables.

1) State variables limits

These are voltage magnitude of load buses, voltage angle of all buses, minus the slack bus, and reactive power output of synchronous generator:

$$V_{Di}^{\min} \le V_{Di} \le V_{Di}^{\max} \tag{12}$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \tag{13}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{14}$$

2) Control variable limits

These limits are for all the control variables of reactive power controllers such as tap position of tap-changer transformers, capacitor and SVC reactive power capabilities, but also the voltage magnitude of synchronous generator buses:

$$T_i^{\min} \le T_i \le T_i^{\max} \tag{15}$$

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max} \tag{16}$$

$$Q_{SVCi}^{\min} \le Q_{SVCi} \le Q_{SVCi}^{\max} \tag{17}$$

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \tag{18}$$

3) Fixed variables: powers limits of Wind turbine

$$P_{WTi}^{\min} \le P_{WTi} \le P_{WTi}^{\max} \tag{19}$$

$$Q_{WTi}^{\min} \le Q_{WTi} \le Q_{WTi}^{\max} \tag{20}$$

Where: P_{Loss} is the total active power losses. g_L is the line conductance. V_i, V_j, δ_i and δ_j are the voltage magnitudes at buses i, j, and their angles respectively. δ_{ij} is the voltage angle difference between V_i and V_j. NL and NB are respectively, the number of lines and buses. ε_V is the average of voltage deviations of power demand buses, V_{Di} is the voltage of power demand bus i and $V_{i,nom}$ its nominal voltage. ND is the number of power demand buses. $P_{Gi,WTi}$ is the active power generated by the synchronous generator or wind turbine, and $Q_{Gi,WTi}$ is the reactive power generated by the synchronous generator or absorbed by the wind turbine. $|Y_{ij}|$ is the magnitude of bus admittance element i,j and θ_{ij} its angle. P_{Di} and Q_{Di} are respectively, the active and reactive powers demand at bus i. V_{Gi} is the voltage magnitude at synchronous generator bus i. Q_{Ci} and Q_{SVCi} are respectively, the reactive powers generated by fixed capacitor and SVC at bus i, T_i and tap-position of tap-changer transformers at the same bus i. the superscripts *max* and *min* mean maximal and minimal variable limits.

IV. OVERVIEW OF THE PROPOSED ALGORITHM

A. Particle swarm algorithm principle

PSO algorithm was introduced by Kennedy and Eberhart in 1995 [4] as an alternative to genetic algorithm (GA). The PSO algorithm motivation was the social behaviour such as bird flocking and fish schooling. This algorithm can be effectively used in solving many nonlinear hard optimization problems [11]. Unlike many traditional mathematical methods, this optimization method does not need any gradient information about the objective or error function and it can obtain the best solution independently [4, 11]. This method is also less dependent on the initial starting point in order get the global optimal solution.

From an initial position, a swarm of particles starts flying in the search space exploring optimal points. Each particle position represents a potential solution. Therefore, the performance of each particle position is evaluated by the fitness function which is the objective function in this work. Our problem having minimization purpose, the best particle is the one with lower fitness value. During the flight (iterations), the best experiences (positions) for each particle is stored in its memory and called personal best (Pbest). The lowest value of all the Pbests, determines the global best (Gbest) of the swarm.

Now, using these two concepts, each particle velocity is updated as :

$$V_i^{t+1} = WV_i^t + C_1 r_1 \left(X_i^{pbest} - X_i^t\right) + C_2 r_2 \left(X^{Gbest} - X_i^t\right) \tag{21}$$

Where

- V_i^{t+1} : Particle velocity at new iteration (t+1)
- V_i^t : Particle velocity at current iteration t
- W : Inertia weight
- C_1, C_2 : Acceleration coefficients
- r_1, r_2: Two separately random numbers between [0, 1]

Therefore, the new particle position is obtained by:

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{22}$$

B. Fitness function of the case problem

In this work, the three objective functions are weighted in one cost function. To deal with constraints, penalty approach is adopted. All equalities and inequalities constraints are penalized in the three objective functions. Therefore, the particle fitness $F(X_i)$ of this problem becomes a multi-objective penalty function, and is given as below:

$$F(X_i) = w_1 P_{loss}(X_i) + w_2 \varepsilon_V(X_i) + w_3 R_{QSVC}(X_i) + P(X_i) \tag{23}$$

Where

- X_i : The position of the particle i in our problem dimension (equals the number of variables).
- w_1, w_2, w_3 : Weights of the three objective functions, respectively. More importance is put to the active power losses, followed by the voltage deviations and SVC reactive power reserve. Hence, $w_1 = 0.7$, $w_2 = 0.2$ and $w_3 = 0.1$
- $P(X_i)$ is the penalty term formulated as follows:

$$P(X_i) = P_{\Delta P} + P_{\Delta Q} + P_{V_D} + P_{VG} + P_T + P_{Qc} + P_{Qscv} + P_{QG} + P_\delta \tag{24}$$

Where

$$P_{\Delta P} = \beta \sum_{i=1}^{NPV-1} (\Delta P)^2 \tag{25}$$

$$P_{\Delta Q} = \beta \sum_{i=1}^{NPQ} (\Delta Q)^2 \tag{26}$$

$$P_{V_D} = \lambda \sum_{i=1}^{ND} \left\{\max\left(0, V_{Di} - V_{Di}^{\max}\right)\right\}^2 + \lambda \sum_{i=1}^{ND} \left\{\max\left(0, V_{Di}^{\min} - V_{Di}\right)\right\}^2 \tag{27}$$

$$P_{VG} = \lambda \sum_{i=1}^{NPV-1} \left\{\max\left(0, V_{Gi} - V_{Gi}^{\max}\right)\right\}^2 + \lambda \sum_{i=1}^{NPV-1} \left\{\max\left(0, V_{Gi}^{\min} - V_{Gi}\right)\right\}^2 \tag{28}$$

$$P_T = \lambda \sum_{i=1}^{NT} \left\{\max\left(0, T_i - T_i^{\max}\right)\right\}^2 + \lambda \sum_{i=1}^{NT} \left\{\max\left(0, T_i^{\min} - T_i\right)\right\}^2 \tag{29}$$

$$P_{Qc} = \lambda \sum_{i=1}^{NQc} \left\{\max\left(0, Q_{Ci} - Q_{Ci}^{\max}\right)\right\}^2 + \lambda \sum_{i=1}^{NQc} \left\{\max\left(0, Q_{Ci}^{\min} - Q_{Ci}\right)\right\}^2 \tag{30}$$

$$P_{QSVC} = \lambda \sum_{i=1}^{NQSVC} \left\{\max\left(0, Q_{SVCi} - Q_{SVCi}^{\max}\right)\right\}^2 + \lambda \sum_{i=1}^{NQSVC} \left\{\max\left(0, Q_{SVCi}^{\min} - Q_{SVCi}\right)\right\}^2 \tag{31}$$

$$P_{QG} = \lambda \sum_{i=1}^{NPV-1} \left\{\max\left(0, Q_{Gi} - Q_{Gi}^{\max}\right)\right\}^2 + \lambda \sum_{i=1}^{NPV-1} \left\{\max\left(0, Q_{Gi}^{\min} - Q_{Gi}\right)\right\}^2 \tag{32}$$

$$P_\delta = \lambda \sum_{i=1}^{NPV-1} \left\{\max\left(0, \delta_i - \delta_i^{\max}\right)\right\}^2 + \lambda \sum_{i}^{NPV-1} \left\{\max\left(0, \delta_i^{\min} - \delta_i\right)\right\}^2 \tag{33}$$

Where: NPV-1 is the number of PV (synchronous generators) buses minus slack bus, NPQ is the number of PQ bus (for load and wind turbines), ND is the number of demand or load buses. NT is the number of tap-changer transformers, NQc is the number of fixed-capacitors banks, and NQsvc is the number of SVCs. β and λ are penalty factors.

V. DATA DESCRIPTION

To evaluate the effectiveness of the problem results, Wale & Hale 6-bus system is used. The data of generation, load and lines are given in figure 3 [4, 12]. The data of the squirrel-cage induction generator is given in table 1 [9]. In this study, economic penetration impact of wind farm is not considered. Therefore, with the purpose of well analyzing the effect of the wind farm into the grid, a high penetration of 45% is considered. This means, 60MW capacity of wind farm (2.3 MWx26 SCIG) is connected into the transmission network of which the total active load is 135 MW (bus 3, bus 5 and bus 6).

The reactive power consumed by the wind power at these different active power output has been computed from (6). At rated wind farm power output (60 MW) for instance, the reactive power absorbed was computed to be 30.49 MVAR. Hence, an SVC with a range from 0 to 30.5 MVAR has been installed at the wind farm bus.

The impact of wind farm transmission lines and transformers is neglected. The power system base is S_B =100MVA.

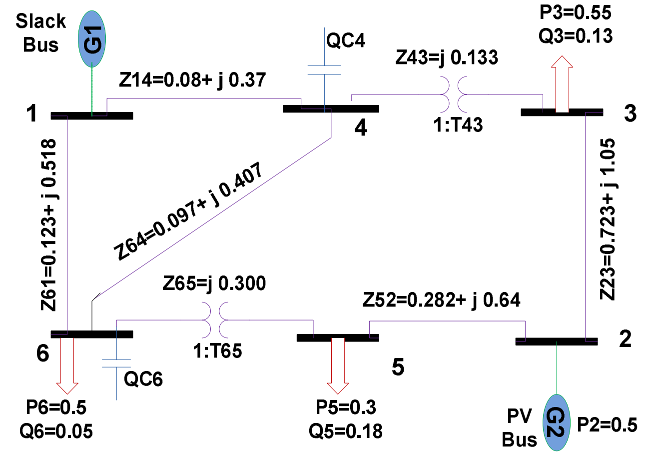

Figure 2 Wale & Hale 6-bus system

Table 1: The 2.3 MW SCIG parameters

Rating power	2.3 MW
Stator voltage (L-L, RMS)	0.69 KV
Number of pair pole	2
Stator resistance	0.006 p.u.
Stator Inductance	0.162 p.u.
Mutual Inductance	3.65 p.u.
Rotor resistance	0.008 p.u.
Rotor inductance	0.06 p.u.

VI. RESULTS AND DISCUSSION

Three different cases have been studied.

To keep the length of the paper reasonable, all optimal control and state variables for these cases are not presented.

A. *Case-I: Optimal solution without SVC compensation considering only active power losses*

In this case, the optimization algorithm is executed before connecting the SVC by considering only the active power losses as objective function.

B. *Case-II: Optimal solution with SVC compensation considering only active power losses*

This case takes now the SVC compensation into account by considering only the active power losses as objective function.

C. *Case-III: Optimal solution with SVC compensation considering all the three objective functions*

This scenario takes into account all the objective functions (active power losses, voltage deviations and SVC reactive power reserve).

The total active power losses, SVC compensation and average of voltage deviations obtained in these cases are respectively presented in figures 3, 4 and 5. The lower and upper voltages are shown in Table 2.

It can be seen from figure 3 that the total active power losses are reduced at the expense of the use of SVC device. However, figure 4 shows that when considering only active power losses as objective function, the tendency of optimization algorithm is to use a maximum SVC compensation in order to achieve as minimal as possible the active power losses. This therefore leads to a null SVC-RPR. Although the active power losses decrease, Table 2 shows that the voltage profile increases considerably from its reference value (1p.u. in this work), and hence the optimality degree of the voltage profile decreases. This can also be seen in figure 5 where the increase of the average of voltage deviations is shown.

When the average of voltage deviations and SVC-RPR are now taken into account during the optimization process, the same figures and table show that the voltage profile is now improved and the SVC-RPR is maximized. But this is achieved at the cost of the active power losses. However, the results reveal that the SVC-RPR is big at low power generation of the wind farm and poor at its high power generation.

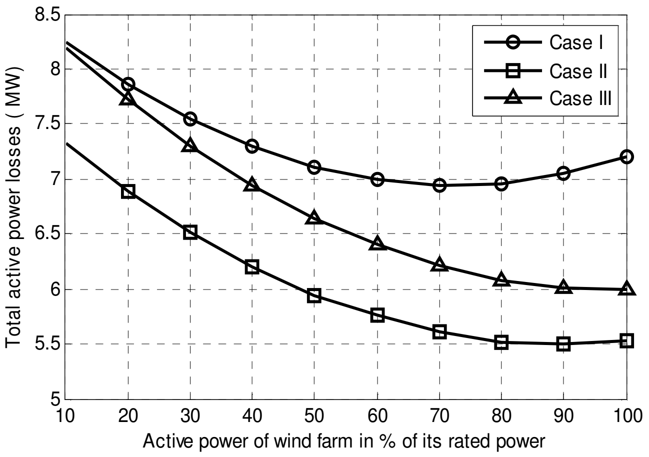

Figure 3 Minimal total active power losses for different wind farm power outputs

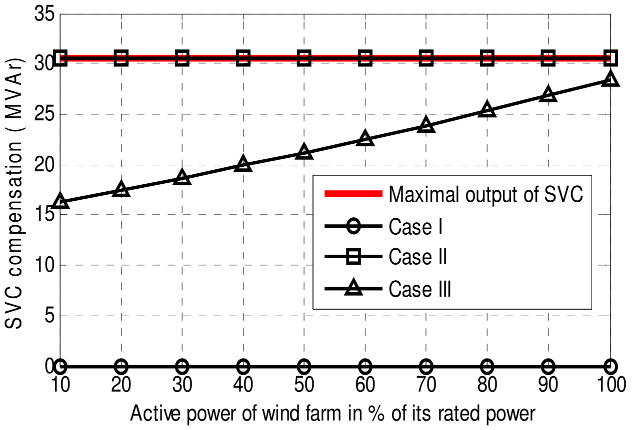

Figure 4 Optimal SVC reactive power output for different wind farm power outputs

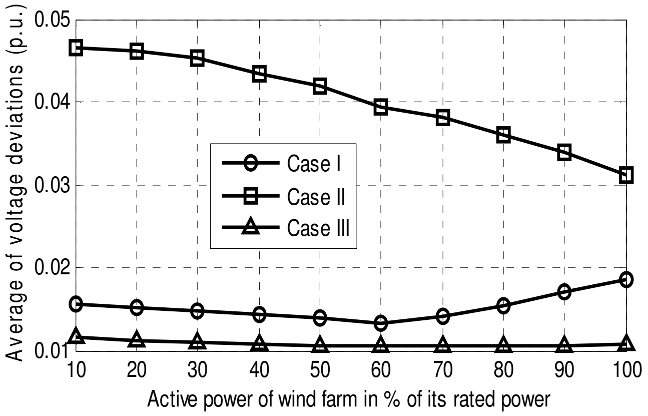

Figure 5 minimal average of voltage deviations at load buses for different wind farm power outputs

Table 2: Lower and upper Voltage for different wind farm output

Wind farm power output		Lower and upper load voltage (p.u.)				
		20%	40%	60%	80%	100%
Case I	min	0.9780	0.9746	0.9703	0.9649	0.9585
	max	1.0264	1.0235	1.0196	1.0147	1.0091
Case II	min	1.0285	1.0291	1.0232	1.0267	1.0244
	max	1.0639	1.0573	1.0562	1.0450	1.0375
Case III	min	0.9862	0.9858	0.9853	0.9845	0.9836
	max	0.9907	0.9918	0.9927	0.9933	0.9936

VII. CONCLUSION

This paper used particle swarm optimization (PSO) algorithm for optimization of reactive power control in a transmission network with a large wind farm connection based on squirrel-cage induction generator.

The results obtained have shown that a good reactive power management in a network with connection of wind farm supported by its SVC may lead to an improvement of voltage profiles, decrease of losses and maximization of SVC-RPR. However, the conflict between the three objective functions has shown the difficulty of achieving a sufficient SVC-RPR during high wind farm power generation, unless the SVC rating is designed to be higher than the reactive power required by the total number of SCIG at full load.

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