Application of Genetic Algorithms for Optimal Reactive Power Planning of Doubly Fed Induction Generators

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Abstract: - This paper describes optimal reactive power control of a doubly fed induction generator (DFIG), which is widely used in a distributed generating plant. Although its structure is similar to that of induction motors, its reactive power control is more complicated. In this paper, steady-state power transfer equations are derived and developed for a doubly fed structure of the induction generators. When a distributed power plant equipped with DFIGs is connected to a regional power grid, reactive power injection from the plant results in distribution system performances, e.g. voltage drop, power losses, etc. By using genetic algorithms, optimal reactive power injection can be achieved in order to minimize total power loss in power distribution systems. The 37-node IEEE standard test feeder is used to evaluate its performances. As a result, optimal reactive power control of DFIGs can reduce total power losses and also improve voltage profiles in power distribution systems.

Key-Words: - Optimal reactive power planning, doubly fed induction generator, optimization, genetic algorithms

1 Introduction

A distributed generator (DG) is a small generator (normally less than 15 MW) [1], scattered throughout an electric power distribution system to serve local loads. It is widely used in a renewable energy plant. The renewable plant has been increasingly installed due to several reasons: i) it can be located closer to customers, ii) high efficiency of modern distributed generating plants is available for a small size capacity of ranging from 10 kW – 15 MW, iii) it is required shorter installation time and cheaper investment cost, iv) it improves distribution reliability, etc [2]. The use of DG in the future requires distribution system engineers to take into account its impact in the system planning. To install a new DG at a particular location, investment and operating costs are very important in power distribution planning. Therefore, one of the planner's goals is to minimize overall cost [3-5]. When the distribution power network structure is assumed to be invariable during the planning period, changes in load energy demand or the appearance of new loads over short period could require some action from existing reactive power equipment or investments for network upgrade might be necessary. In this circumstance, DG has a built-in function to inject desired reactive power to the grid at the point of connection. This leads to the advantage of reducing power losses and can be a valuable option for the planning engineer to reduce investments for the grid upgrade. However, their installation in non-optimal locations or sizing can result both in an increasing of power losses and in a reducing of reliability levels [6]. Analysis of reactive power control for distributed generators at a given location in order to determine an appropriate range of complex power exchanges indicates optimal sizing of DG installation. In this paper, a doubly fed structure of induction generators [7] is investigated. Determination of optimal DG rating is one of constrained optimization problems that can be solved by nonlinear optimization techniques such as sequential quadratic programming (SQP) or intelligent methods like genetic algorithms (GA) [8].

In this paper, Section 2 provides problem formulation of the reactive power planning problems. Brief of power distribution network and doubly fed induction generator models is also included. Section 3 gives solution methodology described step-by-step, particularly the exploitation of GA and the formulation of penalty function. Simulation results and conclusion are in Section 4 and 5, respectively.

2 Problem Formulation

This section describes formulation of reactive power planning. It consists of two major parts: i) power loss model of the power distribution system and ii) reactive power control via DFIG. Both parts are coupled and must be solved accordingly. Although solutions from the power network is directly involved total power losses, reactive power solutions of DG obtained from the power network solver must not be exceeded the reactive power limit of the DFIG. The following gives brief description of both parts.

- *Power Network Solution*

Power flow calculation is to determine a set of voltage solutions that satisfy the power mismatch equation at every node. The main information obtained from this calculation are phasor voltages of load buses, reactive power injection by generator buses, complex power flow through transmission lines, total power losses, etc [9]. Connected generators at generator buses can be modeled as either PV bus or PQ bus. If the voltage magnitude at the point of connection is regulated, the PV bus model can be used. With obtained voltage solutions, the reactive power injected from DFIG can be computed. Reversely, if the reactive power injection is treated as a control variable, DFIG will be assigned as a PQ bus generator with a specified reactive power value. Therefore, the voltage magnitude of the DFIG connection can be obtained. Power network solutions must satisfy a set of nodal power mismatch equations. Given that there is a total of n buses in the system and one of them is assigned as the slack bus. Power flow equations of bus k (real and reactive powers) can be simply expressed as follows.

$$P_{cal,k} = \sum_{i=1}^{n} \left|V_k V_i Y_{ki}\right| cos\left(\theta_{ki} + \delta_i - \delta_k\right) \qquad (1)$$

$$Q_{cal,k} = -\sum_{i=1}^{n} \left|V_k V_i Y_{ki}\right| sin\left(\theta_{ki} + \delta_i - \delta_k\right) \qquad (2)$$

Where

$P_{cal,k}$ and $Q_{cal,k}$ are calculated real and reactive powers of bus k

$|V_k|$ is the voltage magnitude of bus k

δ_k is the phase angle of bus k

$|Y_{ki}|$ is the magnitude of the k^{th}-row, i^{th}-column admittance matrix element

θ_{ki} is the phase angle of the k^{th}-row, i^{th}-column admittance matrix element

The solution of the power network can be obtained by employing some efficient iterative methods, e.g. Gauss-Seidel or Newton-Raphson methods, in order to solve the power mismatch equations, $\Delta P_k = P_{cal,k} - P_{sch,k} = 0$ and $\Delta Q_k = Q_{cal,k} - Q_{sch,k} = 0$ for all nodes, where $P_{sch,k}$ and $Q_{sch,k}$ are scheduled real and reactive powers of bus k.

By applying the Talor Series expansion, the NR method separately approximates the real and reactive power flow equations by collecting the first two terms and neglecting other higher-order terms but there is still some interaction between them. Briefly, (2) and (3) represent real and reactive power mismatch equations at bus k after approximation. By collection of the real and reactive power mismatches of a total of n-1 buses, solution updating equation of the Newton-Raphson

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial P_2}{\partial \delta_n}^{(k)} & \frac{\partial P_2}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial P_2}{\partial |V_n|}^{(k)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial P_n}{\partial \delta_n}^{(k)} & \frac{\partial P_n}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial P_n}{\partial |V_n|}^{(k)} \\ \hline \frac{\partial Q_2}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial Q_2}{\partial \delta_n}^{(k)} & \frac{\partial Q_2}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial Q_2}{\partial |V_n|}^{(k)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \delta_2}^{(k)} & \cdots & \frac{\partial Q_n}{\partial \delta_n}^{(k)} & \frac{\partial Q_n}{\partial |V_2|}^{(k)} & \cdots & \frac{\partial Q_n}{\partial |V_n|}^{(k)} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \qquad (4)$$

power flow method can be written in (4).

In addition, (4) can be reduced to the compact matrix form, so-called Jacobian matrix equation of the power flow solution method as described in (5).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (5)$$

Where

$J_1 - J_4$ are Jacobian sub-matrices

By rearranging (5), phase angle and magnitude of the voltage phasors of n-1 buses can be updated according to the following equations.

$$\begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (6)$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \quad (7)$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \quad (8)$$

- *Reactive Power Control of a Doubly Fed Induction Generator*

A DFIG has a special feature and differs from a conventional induction generator in which its rotor circuit is connected to an adjustable ac source [10] as shown in Fig. 1. Fig. 2 shows the per-phase steady-state equivalent circuit of the DFIG. Its real and reactive power transfer equations can be directly derived from this circuit. Analyzing the DFIG is similar to that of a conventional induction generator. Only a controlled external source E_s is added in the rotor circuit.

Starting with complex power transfer from the induction generator as described in the following expression,

$$S_g^* = P_g - jQ_g = V_t^* I_g \quad (9)$$

and

$$I_g = \frac{\frac{E_s\angle\theta}{s} - V_t\angle 0°}{R_g + jX_g} = \frac{\frac{E_s}{s}(cos\theta + j\,sin\theta) - V_t}{R_g + jX_g} \quad (10)$$

where

$$R_g = r_1 + r_2/s \text{ and } X_g = x_1 + x_2$$

Briefly, expression of real and reactive power exchanges between the DFIG and the supply grid can be written in (11) and (12). These two equations will be used as special constraints during the process of the power network optimization.

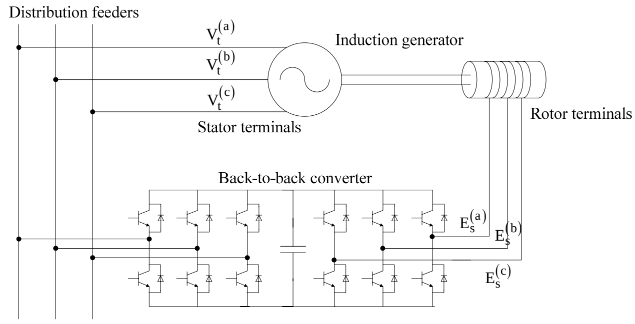

Fig. 1**.** Doubly fed induction generator system

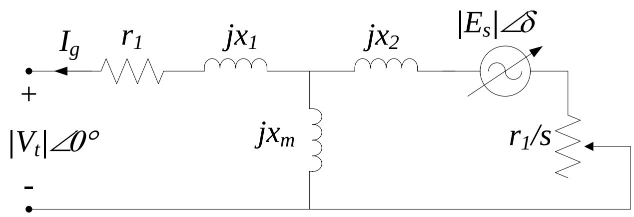

Fig. 2. Per-phase steady-state equivalent circuit of the DFIG

$$P_g = \frac{\frac{|V_t E_s|}{s}\left(r_1 + \frac{r_2}{s}\right)cos\,\delta + \frac{|V_t E_s|}{s}(x_1 + x_2)\,sin\,\delta - \left(r_1 + \frac{r_2}{s}\right)|V_t|^2}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad (11)$$

$$Q_g = \frac{\frac{|V_t E_s|}{s}(x_1 + x_2)\,cos\,\delta - \frac{|V_t E_s|}{s}\left(r_1 + \frac{r_2}{s}\right)sin\,d - (x_1 + x_2)|V_t|^2}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad (12)$$

From the above equations where all machine parameters are fixed, there are three variables that can be controlled: i) $|E_s|$, ii) δ and iii) slip (s). In some applications, constant speed operation might be held. Therefore, controlling through $|E_s|$ and δ are more generalized. These two variables can be achieved by a specially designed voltage controller of the back-to-back converter as in Fig. 1.

With regulating the real power injection from the DFIG, reactive power can be varied according to $|E_s|$ and δ adjustment. When constant real power generation is taken into account, a specified value of the reactive power yields only one pair of $|E_s|$ and δ. This results in Fig. 3 representing δ in horizontal axis without showing $|E_s|$.

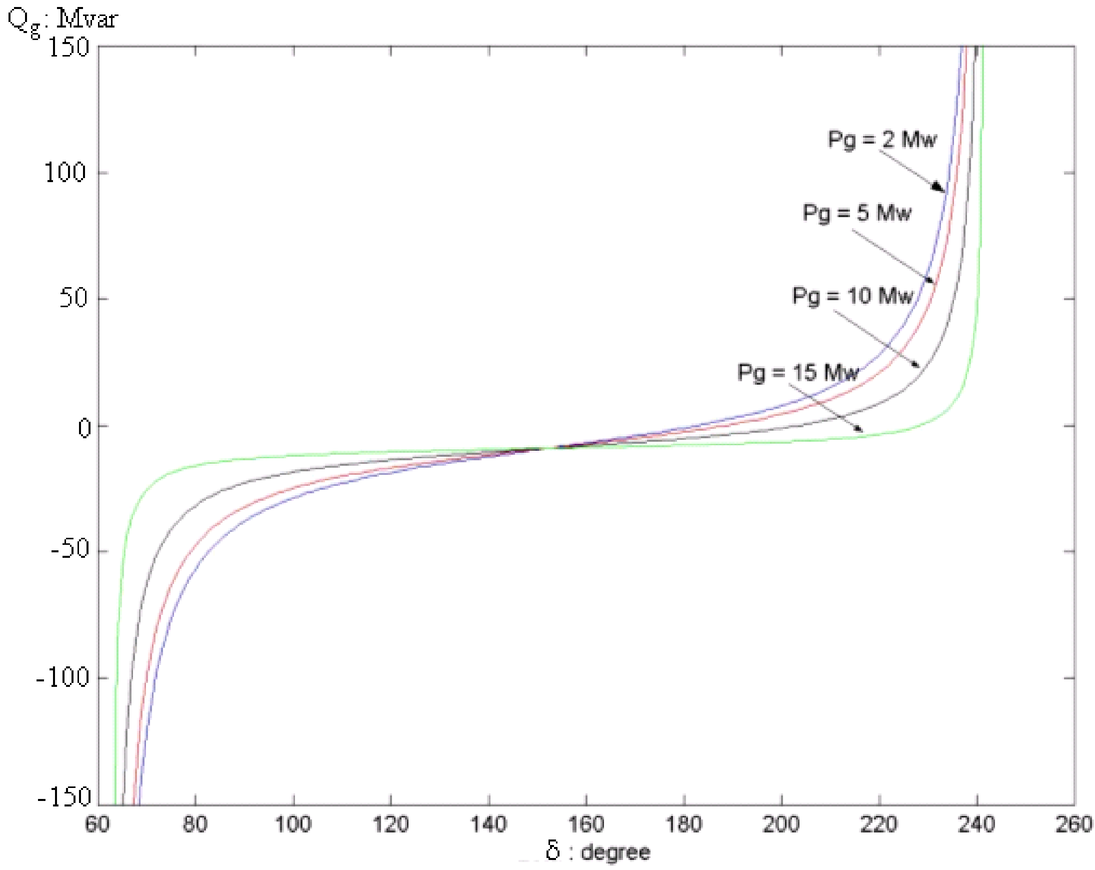

Fig. 3. DFIG's reactive power control of constant real power operation where r_1 = 3.4 Ω, r_2 = 0.43 Ω, x_1 = 3.5 Ω, x_2 = 0.35 Ω, s = 4.0%

3 Optimal Reactive Power Planning

Minimizing the overall power losses in during normal operation of an electric power distribution system requires some efficient optimization techniques. It can be formulated as follows.

Minimize $$P_{loss} = \sum_{i=1}^{m} |I_i|^2 r_i$$

Subject to
$$P_{sch,k} - P_{cal,k} = 0, k = 1,2,...,n$$
$$Q_{sch,k} - Q_{cal,k} = 0, k = 1,2,...,n$$
$$Equation(3) = 0$$
$$Equation(4) = 0$$
$$Q_g^{min} \le Q_g \le Q_g^{max}$$
$$V_{min} \le |V_i| \le V_{max}, i = 1,2,...,n$$
$$E_{min} \le |E_s| \le E_{max}$$
$$\delta_{min} \le \delta \le \delta_{max}$$

Where r_i denotes the resistance of feeder i
I_i denotes the current flowing through feeder i
m is a total number of feeder lines
P_g is a fixed value of DFIG's real power
Q_g is a control variable

To solve the above constrained optimization problem, a penalty function combining the objective function together with all constrained is applied. The quadratic function is used to penalize all the above constraints. In this paper, genetic algorithms will be employed. It can be described as follows.

Genetic algorithms [8, 11-14] are one of the well-known intelligent search mechanism based on the Darwinian principle of natural selection. It consists of bit strings representing the control variables and three genetic operators: i) selection or reproduction, ii) crossover and iii) mutation. The algorithm starts with a random creation of an initial population. During each generation, the strings within the current population are evaluated for their fitness values via the objective function. A new population, so-called offspring, is then created using these three genetic operators. This stochastic process is intended to generate a new and better population from the old population. Assuming the algorithm converges, a set of solutions with better fitness is obtained. Thus, the optimal solution is found. It can be summarized step-by-step as follows.

Given that a population set has *N* members and each member consists of *M* variables. Each individual member of the population is called a chromosome.

1. Initialization: Generate an initial population by using random process and then evaluate their corresponding fitness function.
2. Evolution: Apply the genetic operators to create an offspring population.
3. Fitness test: Evaluate the fitness value for the generated offspring population.
4. Convergence check: Check for violation of all termination criteria. If not satisfied, repeat the evolution process.

It can be summarized in Fig. 4.

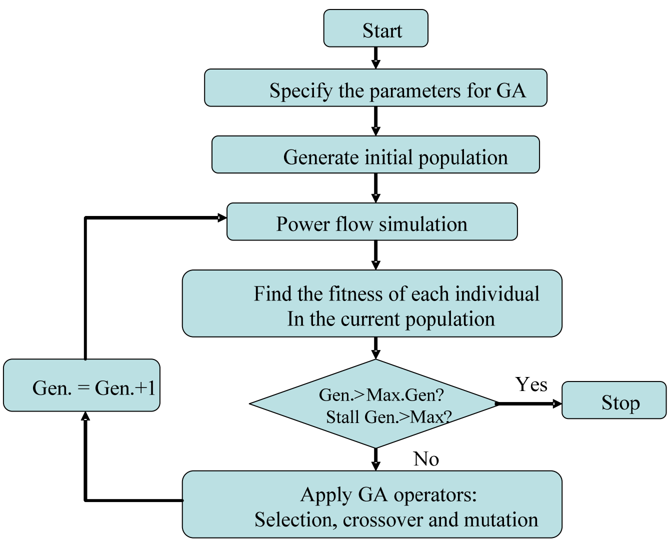

Fig. 4. Flowchart of the GA procedure [11]

In this paper, the GA is selected to build up an algorithm to solve optimal reactive power flow problems. To reduce programming complication, the Genetic Algorithm (GADS TOOLBOX in MATLAB [15]) is employed to generate a set of initial random parameters. With the searching process, the parameters are adjusted to give the best result.

5 Simulation Results

To evaluate the proposed reactive power control scheme, the 37-node IEEE standard test feeder [16] as shown in Fig. 4 was used for test. All day operation and reactive power compensation performed by the DFIG at a specific location in order to minimize the total power losses were situated. Four test case scenarios were conducted as: i) base case of no DFIG installed, ii) DFIG installed at node 8, iii) DFIG installed at node 25 and iv) DFIGs installed at node 8 and 25.

In addition, the real power injection by the DFIG is fixed for each case by 5 MW and 10 MW. Therefore, there is a total of eight test case scenarios. Applying genetic algorithms, the optimal solution for each case can be obtained. Furthermore, these solutions are compared with the solution obtained by a case of zero reactive power injection and the base case. All results can be shown in Tables 1 and 2 as follows.

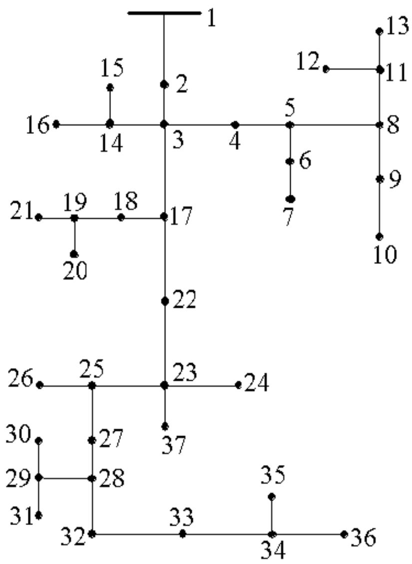

Fig. 5 37-node IEEE standard test feeder

Table 1 Optimal solutions in which each P_g = 5 MW was fixed

Location	Without DFIG	Q_g = 0 Mvar	Optimal Q_g
Bus 8	144.91 MWh	131.96 MWh	121.24 MWh
Bus 25	144.91 MWh	127.01 MWh	110.72 MWh
Bus 8 & 25	144.91 MWh	114.88 MWh	104.35 MWh

Table 2 Optimal solutions in which each P_g = 10 MW was fixed

Location	Without DFIG	Q_g = 0 Mvar	Optimal Q_g
Bus 8	144.91 MWh	121.05 MWh	109.22 MWh
Bus 25	144.91 MWh	111.41 MWh	91.51 MWh
Bus 8 & 25	144.91 MWh	90.72 MWh	81.31 MWh

Moreover, with 30 trials of each case, the best solution of which obtained from each can be illustrated in Tables 3 – 6.

Table 3 Optimal solutions in which P_g = 5 MW was installed at bus 8

Hour	Total load (MW)	Power losses (MW)			Optimal Q_g (Mvar)
		Before installation	Unity power factor	Optimal Q_g	
1	72.33	4.22	3.81	3.40	11.79
2	71.26	4.12	3.71	3.31	11.80
3	73.78	4.42	3.99	3.58	11.78
4	76.52	4.72	4.27	3.85	11.76
5	81.64	5.33	4.84	4.41	11.72
6	86.59	6.01	5.47	5.02	12.49
7	92.98	6.98	6.38	5.91	12.44
8	98.61	7.88	7.23	6.74	12.38
9	94.48	7.20	6.60	6.12	12.43
10	87.91	6.17	5.63	5.17	12.48
11	83.47	5.51	5.00	4.57	11.70
12	80.45	5.22	4.74	4.31	11.72
13	80.85	5.19	4.71	4.29	11.73
14	81.63	5.21	4.72	4.30	11.73
15	82.71	5.51	5.01	4.58	11.70
16	85.31	5.79	5.27	4.84	11.67
17	89.16	6.37	5.80	5.34	12.48
18	95.05	7.28	6.65	6.18	12.43
19	100.41	8.17	7.50	7.00	12.34
20	106.31	9.28	8.54	8.02	12.31
21	98.23	7.77	7.11	6.62	12.39
22	90.20	6.44	5.86	5.39	12.47
23	82.60	5.41	4.90	4.47	11.71
24	76.68	4.70	4.24	3.83	11.76
Total Losses		144.91	131.96	121.24	-

Table 4 Optimal solutions in which P_g = 5 MW was installed at bus 25

Hour	Total load (MW)	Power losses (MW)			Optimal Q_g (Mvar)
		Before installation	Unity power factor	Optimal Q_g	
1	72.33	4.22	3.64	3.04	11.66
2	71.26	4.12	3.55	2.96	11.65
3	73.78	4.42	3.83	3.22	11.64
4	76.52	4.72	4.10	3.49	11.63
5	81.64	5.33	4.65	4.02	11.58
6	86.59	6.01	5.26	4.62	11.51
7	92.98	6.98	6.15	5.48	11.32
8	98.61	7.88	6.97	6.30	11.00
9	94.48	7.20	6.35	5.68	11.22
10	87.91	6.17	5.41	4.77	11.49
11	83.47	5.51	4.81	4.18	11.57
12	80.45	5.22	4.54	3.92	11.59
13	80.85	5.19	4.52	3.90	11.59
14	81.63	5.21	4.54	3.92	11.59
15	82.71	5.51	4.80	4.17	11.54
16	85.31	5.79	5.06	4.43	11.52
17	89.16	6.37	5.59	4.94	11.45
18	95.05	7.28	6.42	5.75	11.22
19	100.41	8.17	7.24	6.57	10.91
20	106.31	9.28	8.25	6.56	11.03
21	98.23	7.77	6.87	6.20	11.16
22	90.20	6.44	5.66	5.01	11.44
23	82.60	5.41	4.73	4.11	11.58
24	76.68	4.70	4.09	3.48	11.61
Total Loss		144.91	127.01	110.72	-

Table 5 Optimal solutions in which P_g = 5 MW was installed at bus 8 and 25

Hour	Total load (MW)	Power losses (MW)			Optimal Q_g (Mvar)	
		Before installation	Unity power factor	Optimal Q_g	@ bus 8	@ bus 25
1	72.33	4.22	3.26	2.41	10.98	12.39
2	71.26	4.12	3.18	2.33	10.98	12.40
3	73.78	4.42	3.43	2.57	10.97	12.36
4	76.52	4.72	3.67	2.80	10.96	12.32
5	81.64	5.33	4.18	3.29	10.98	12.32
6	86.59	6.01	4.75	3.83	10.98	12.29
7	92.98	6.98	5.58	4.62	10.97	12.22
8	98.61	7.88	6.35	5.36	10.94	12.11
9	94.48	7.20	5.78	4.80	10.96	12.19
10	87.91	6.17	4.90	3.97	10.98	12.28
11	83.47	5.51	4.33	3.43	10.98	12.31
12	80.45	5.22	4.09	3.20	10.97	12.32
13	80.85	5.19	4.07	3.18	10.97	12.32
14	81.63	5.21	4.08	3.19	10.98	12.32
15	82.71	5.51	4.34	3.43	10.98	12.31
16	85.31	5.79	4.57	3.66	10.98	12.30
17	89.16	6.37	5.05	4.12	10.99	12.27
18	95.05	7.28	5.83	4.86	10.97	12.19
19	100.41	8.17	6.60	5.59	10.94	12.07
20	106.31	9.28	7.56	6.51	10.86	11.88
21	98.23	7.77	6.26	5.26	10.96	12.13
22	90.20	6.44	5.11	4.18	10.99	12.27
23	82.60	5.41	4.25	3.35	10.99	12.32
24	76.68	4.70	3.66	2.79	10.97	12.32
Total Loss		144.91	114.88	92.73	-	-

Table 6 Optimal solutions in which P_g = 10 MW was installed at bus 8

Hour	Total load (MW)	Power losses (MW)			Optimal Q_g (Mvar)
		Before installation	Unity power factor	Optimal Q_g	
1	72.33	4.22	3.47	3.03	17.70
2	71.26	4.12	3.38	2.94	17.66
3	73.78	4.42	3.64	3.19	17.75
4	76.52	4.72	3.89	3.43	17.83
5	81.64	5.33	4.42	3.95	18.01
6	86.59	6.01	5.01	4.52	18.23
7	92.98	6.98	5.87	5.36	18.56
8	98.61	7.88	6.67	6.13	18.84
9	94.48	7.20	6.08	5.55	18.64
10	87.91	6.17	5.16	4.67	18.29
11	83.47	5.51	4.57	4.09	18.06
12	80.45	5.22	4.34	3.86	18.00
13	80.85	5.19	4.31	3.84	17.97
14	81.63	5.21	4.31	3.84	17.96
15	82.71	5.51	4.60	4.12	18.11
16	85.31	5.79	4.84	4.35	18.17
17	89.16	6.37	5.32	4.82	18.34
18	95.05	7.28	6.12	5.60	18.64
19	100.41	8.17	6.91	6.36	18.93
20	106.31	9.28	7.90	7.32	19.33
21	98.23	7.77	6.55	6.01	18.79
22	90.20	6.44	5.36	4.86	18.33
23	82.60	5.41	4.46	3.99	18.01
24	76.68	4.70	3.86	3.40	17.80
Total Loss		144.91	121.05	109.22	-

Table 7 Optimal solutions in which P_g = 10 MW was installed at bus 25

Hour	Total load (MW)	Power losses (MW)			Optimal Q_g (Mvar)
		Before installation	Unity power factor	Optimal Q_g	
1	72.33	4.22	3.15	2.39	22.81
2	71.26	4.12	3.07	2.32	22.77
3	73.78	4.42	3.32	2.56	22.88
4	76.52	4.72	3.56	2.78	22.97
5	81.64	5.33	4.05	3.25	23.18
6	86.59	6.01	4.61	3.78	23.44
7	92.98	6.98	5.41	4.54	23.82
8	98.61	7.88	6.16	5.25	24.16
9	94.48	7.20	5.59	4.71	23.92
10	87.91	6.17	4.74	3.91	23.50
11	83.47	5.51	4.21	3.40	23.23
12	80.45	5.22	3.95	3.16	23.16
13	80.85	5.19	3.94	3.14	23.13
14	81.63	5.21	3.96	3.17	23.10
15	82.71	5.51	4.18	3.37	23.28
16	85.31	5.79	4.43	3.61	23.36
17	89.16	6.37	4.90	4.06	23.56
18	95.05	7.28	5.66	4.78	23.92
19	100.41	8.17	6.42	5.50	24.26
20	106.31	9.28	7.34	6.37	24.73
21	98.23	7.77	6.08	5.18	24.11
22	90.20	6.44	4.98	4.14	23.56
23	82.60	5.41	4.14	3.34	23.18
24	76.68	4.70	3.56	2.79	22.96
Total Loss		144.91	111.41	91.51	-

Table 8 Optimal solutions in which P_g = 10 MW was installed at bus 8 and 25

Hour	Total load (MW)	Power losses (MW)			Optimal Q_g (Mvar)	
		Before installation	Unity power factor	Optimal Q_g	@ bus 8	@ bus 25
1	72.33	4.22	2.53	1.66	10.70	18.96
2	71.26	4.12	2.46	1.59	10.69	18.92
3	73.78	4.42	2.66	1.78	10.74	19.01
4	76.52	4.72	2.85	1.96	10.78	19.09
5	81.64	5.33	3.27	2.35	10.87	19.26
6	86.59	6.01	3.74	2.80	10.97	19.47
7	92.98	6.98	4.44	3.44	11.14	19.78
8	98.61	7.88	5.09	4.06	11.29	20.06
9	94.48	7.20	4.60	3.60	11.17	19.87
10	87.91	6.17	3.86	2.91	11.00	19.52
11	83.47	5.51	3.39	2.47	10.89	19.30
12	80.45	5.22	3.20	2.29	10.85	19.25
13	80.85	5.19	3.18	2.27	10.84	19.22
14	81.63	5.21	3.19	2.28	10.85	19.19
15	82.71	5.51	3.41	2.48	10.89	19.36
16	85.31	5.79	3.60	2.66	10.94	19.40
17	89.16	6.37	3.99	3.03	11.04	19.56
18	95.05	7.28	4.64	3.64	11.19	19.85
19	100.41	8.17	5.30	4.25	11.36	20.12
20	106.31	9.28	6.12	5.02	11.55	20.51
21	98.23	7.77	5.00	3.98	11.28	20.00
22	90.20	6.44	4.04	3.0732	11.06	19.54
23	82.60	5.41	3.32	2.3987	10.89	19.24
24	76.68	4.70	2.84	1.9473	10.77	19.06
Total Loss		144.91	90.72	67.93	-	-

As a result, when reactive power injected from the DFIG is well controlled, operation with minimum power losses can be expected. For a case of P_g = 5 MW, the maximum power loss reduction is just over 40 MWh. Whilst, about 60 MWh energy reduction is obtained from the other case. Imagine that Suranaree University of Technology (SUT) consumes 2 MW average power demand per hour, i.e. a total of 48-MWh electric energy is consumed every day. The total amount of energy loss reduction from the proposed reactive power control scheme is sufficient to feed the SUT campus for a whole day.

6 Conclusion

This paper presents effects of a doubly fed induction generator on power loss reduction in an electric power distribution system. Appropriate adjustment of the reactive power injection from an available DFIG results in total power losses and voltage distribution along feeder lines. In addition, real and reactive power transfers of a DFIG are included to formulate a constrained optimization problem. With both constraints the obtained solution is verified for practical use due to the limitation of voltage fed by the back-to-back converter. Genetic algorithms are very useful in this problem due to its ability of finding a near global solution. From satisfactory results, optimal reactive power control of a doubly fed induction generator can considerably reduce total power losses of the electric power distribution feeder. It is confirmed by the results of the 37-node IEEE standard test feeder described in this paper.

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