

MINIMIZING POWER LOSSES OF SEIG USING CONSTRAINED PARTICLE SWARM OPTIMIZATION CONSIDERING VOLTAGE REGULATION

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Abstract: Induction generators are widely used in various applications since they offer distinct advantages over conventional synchronous machines, resulting in a simplified design, installation at lower capital cost and substantial savings in operation and maintenance expenses. The wind turbine induction generator system is proposed to supply isolated loads under widely varying conditions. These conditions are the wind speed and load variations. Under these varying conditions, there will be some changes in the terminal generated voltage. The terminal voltage can be regulated by adapting the value of excitation capacitance required for the induction generator.

This paper presents a Constrained Particle Swarm Optimization technique for minimizing the power losses of self excited induction generator with terminal voltage control under operating conditions by selecting the suitable capacitance required for the generator excitation.

Testing of the proposed technique over conventional Particle Swarm Technique is performed. Results signify the supremacy of the proposed technique over conventional particle swarm optimization technique.

Keywords: Self Excited Induction Generator, Particle Swarm optimization, Constrained Particle Swarm optimization, Power losses minimization, Voltage Control.

Nomenclature

R_S, R_R, R_L	p.u stator, rotor and load resistances, respectively,
X_S, X_R, X_M, X_L, X_C	p.u stator, rotor leakage, magnetizing, load and exciting reactances, at base frequency, respectively,
f_s	synchronous frequency,
F	p.u frequency,
v	p.u rotational speed,
E_g, V_T	p.u air gap and terminal voltages, respectively,
I_S, I_L	p.u stator and load currents per phase, respectively,
N	number of dimensions in a particle,
I	number of particles,
w	inertia weight factor,
t	pointer of iterations,
c_1, c_2	accelerating constants,

$\text{rand}_1, \text{rand}_2$	uniform random values in the range of [0,1],
v	velocity of the j^{th} dimension in the i^{th} particle,
$V_{ij}^{(t)}$	current position of the j^{th} dimension in the i^{th} particle at iteration t ,
$P_{ij}^{(t)}$	both random numbers called initial and final weights,
w_{max} and w_{min}	maximum number of iterations,
t_{max}	current iteration number,
t	

1. Introduction

Several coastal regions in Middle East are exposed to immense level of wind energy most of the year, which makes the utilization of wind energy a promising solution to generate electricity with zero harmful emission (Green System) [1-2].

Stand alone self-excited three phase induction generators have gained increased interest in the range of low power due to their low prices, rugged construction, and low maintenance requirements [3-4]. Unfortunately, the generated output voltage is dependent on wind speed, loading conditions and the excitation capacitance itself. This requires regulation of the terminal voltage of the generator [5-6].

Several optimization techniques have been reported in the literature. The suitability of using a normal three-phase induction motor as a capacitor self-excited induction generator has been illustrated [7-8]. For this design procedure, the air gap flux density and the current densities of the rotor and the stator must be specified by the designer [9]. Steady state performance analysis of a capacitor excited induction generator was compared with commercially designed line excited induction generator operating as Self Excited Induction Generator (SEIG), [10]. Steady state analysis using an

iterative method for determination of per unit frequency was performed [11]. Simulated Annealing approach was suggested for solving voltage regulation optimization problem [12]. Constrained Optimization (CO) problems are encountered in numerous applications. Structural optimization, engineering design, economics, and allocation problems are just a few of the scientific fields in which CO problems are frequently met [13-14]. The CO problem can be represented as the following nonlinear programming problem:

$$\min f(x) \quad (1)$$

Where $f(x)$ is the objective function, subjected to the linear or nonlinear constraints

$$g_i(x) \leq 0, \quad i = 1, \dots, m \quad (2)$$

The formulation of the constraints in (2) is not restrictive, since an inequality constraint of the form $g_i(x) \geq 0$, can also be represented as $-g_i(x) \leq 0$, and an equality constraint, $g_i(x) = 0$, can be represented by two inequality constraints $g_i(x) \leq 0$ and $-g_i(x) \leq 0$.

The most common approach for solving CO problems is the use of a penalty function. The constrained problem is transformed to an unconstrained one, by penalizing the constraints and building a single objective function, which in turn is minimized using unconstrained optimization algorithms [14].

In this paper, the value of the excitation capacitance required for SEIG is calculated to minimize the power losses with terminal voltage control using Constrained Particle Swarm Optimization (CPSO). Two different loading conditions, R and R-L loads with speed variations are used to test the competence of the proposed method over particle Swarm Optimization (PSO).

2. Steady State Analysis of Self-Excited Induction Generators

Fig. 1 shows the per-phase equivalent circuit commonly used for SEIG supplying resistive load (first case). A three-phase induction machine can be operated as a SEIG if its rotor is externally driven at a suitable speed

and a three-phase capacitor bank of a sufficient value is connected across its stator terminals. When the induction machine is driven at the required speed, the residual magnetic flux in the rotor will induce a small e.m.f. in the stator winding. The appropriate capacitor bank causes this induced voltage to continue to increase until an equilibrium state is attained due to magnetic saturation of the machine.

When SEIG is loaded, both the magnitude and frequency of the induced e.m.f are affected by: the prime mover speed, the capacitance of the capacitor bank and the load impedance.

The steady-state per-phase equivalent circuit of a SEIG, supplying a balanced resistive load, is shown in Fig. 1.

From Fig. 1, the total current at node a, may be given by:

$$E_1(Y_1 + Y_M + Y_R) = 0 \quad (3)$$

Therefore, under steady-state self-excitation, the total admittance must be zero, since

$$E_1 \neq 0 \text{ so}$$

$$(Y_1 + Y_M + Y_R) = 0 \quad (4)$$

or

$$\text{Real}(Y_1 + Y_M + Y_R) = 0 \text{ and } \text{Imag}(Y_1 + Y_M + Y_R) = 0 \quad (5)$$

Where

$$Y_1 = \frac{(Y_L + Y_C)Y_S}{Y_L + Y_C + Y_S} \quad Y_C = \frac{1}{-j(X_C / F^2)}$$

$$Y_S = \frac{1}{(R_S / F) + jX_S} \quad Y_L = \frac{1}{(R_L / F)}$$

$$Y_R = \frac{1}{\frac{R_R}{F - V} + jX_R} \quad Y_M = \frac{1}{jX_M}$$

Equations 5 and 6 are nonlinear for the four unknowns F , X_M , X_C and v . Two of these unknowns should be specified. The other two unknowns can be found by solving the two non linear equations. Different values of rotational speed v and the controlled value of the capacitance X_C are determined to control the output voltage then the frequency and X_M are calculated. Based on the analysis introduced in [15-16], a fifth order polynomial independent of X_M is extracted to calculate

the frequency, then the values of X_M are calculated at different loading conditions.

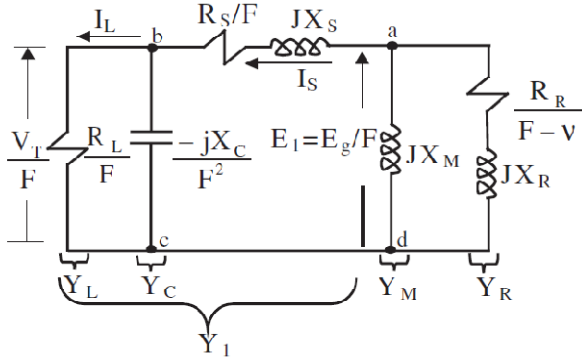


Fig. 1, Per-phase equivalent circuit of a SEIG.

The relationship between the magnetizing reactance X_M and the air-gap voltage E_g/F of the machine based on [15] is given by:

$$E_1 = \frac{E_g}{F} = 1.12 + 0.078X_M - 0.146X_M^2 \quad (6)$$

After calculating the air gap voltage E_1 , the stator and load currents I_s and I_L respectively can be calculated as

$$I_s = E_1 \times Y_1 \quad (7)$$

$$I_L = I_s \frac{Y_L}{Y_L + Y_C} \quad (8)$$

then the input and output power can be calculated as

$$P_{in} = 3|E_1 \times Y_R|^2 \times \frac{R_R}{F-v} \quad (9)$$

$$P_{out} = 3|I_L|^2 \times \frac{R_L}{F} \quad (10)$$

The difference between the input and output power is the losses of the SEIG and can be calculated as :

$$P_{Loss} = P_{in} - P_{out} \quad (11)$$

Some modifications of the foregoing equations are performed to include R-L load (second case).

3. Particle Swarm Optimization Method

PSO is a stochastic global optimization method based on simulation of social behavior. As in genetic algorithm, PSO exploits a population of potential solutions to probe the search space. In contrast to the aforementioned methods in PSO no operators inspired by natural

evolution are applied to extract a new generation of candidate solutions. Instead of mutation, PSO relies on the exchange of information between individuals, called particles, of the population, called swarm. In effect, each particle adjusts its trajectory towards its own previous best position, and towards the best previous position attained by any member of its neighborhood [17]. In the global variant of PSO, the whole swarm is considered as the neighborhood. Thus, global sharing of information takes place and particles profit from the discoveries and previous experience of all other companions during the search for promising regions of the landscape. To visualize the operation of the method, consider the case of the single objective minimization case; promising regions in this case possess lower function values compared to others, visited previously.

Let x and y denote a particle coordinates (position) and its corresponding flight speed (velocity) VV_x in the x direction and VV_y in the y direction. Modification of the individual position is realized by velocity and position information.

PSO algorithm for N -dimensional problem formulation can be described as follows:

Let P be the particle position and VV is the velocity in a search space. Consider i as a particle in the total population (swarm). The i^{th} particle position can be represented as $P_i = (P_{i1}, P_{i2}, P_{i3}, \dots, P_{iN})$ in the N -dimensional space. The best previous position of the i^{th} particle is recorded and represented as $P_{besti} = (P_{besti1}, P_{besti2}, P_{besti3}, \dots, P_{bestij})$. The index of the best particle among all the particles in the group is represented by g_{best} . The velocity i^{th} particle is represented as $VV_i = (VV_{i1}, VV_{i2}, VV_{i3}, \dots, VV_{ij})$. The modified velocity and position of each particle can be calculated using the current velocity and the distance from P_{best} to g_{best} as indicated in following formulas

$$VV_{ij}^{(t+1)} = w * VV_{ij}^{(t)} + c_1 * rand_1 * (P_{bestij} - P_{ij}^{(t)}) + c_2 * rand_2 * (g_{bestj} - P_{ij}^{(t)}) \quad (12)$$

$$P_{ij}^{(t+1)} = P_{ij}^{(t)} + v_{ij}^{(t+1)} \quad (13)$$

$$i = 1, 2, \dots, I \quad \text{and} \quad j = 1, 2, \dots, N$$

Inertia weighting factor w has provided improved performance when using the linearly decreasing [17]. Its value is decrease linearly from about 1.2 to 0.1 during a run. Suitable selection of w provides a balance between global and local exploration and exploitation, and results

in less iteration on average to find a sufficiently optimal solution. Its value is set according to the following equation:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{t_{\max}} * t \quad (14)$$

In (14), the first term indicates the current velocity of the particle, second term represents the cognitive part of PSO where the particle changes its velocity based on its own thinking and memory. The third term represents the social part of PSO where the particle changes its velocity based on the social-psychological adaptation of knowledge [17].

4. The Penalty Function Approach

The search space in constrained problems consists of two kinds of points: feasible and unfeasible. Feasible points satisfy all the constraints, while unfeasible points violate at least one of them. The Penalty Function technique solves the problem through a sequence of unconstrained optimization problems [18]. Up to date, no other method for defining pertinent penalty functions, than trial and error, exists [13].

Penalty functions are distinguished into two main categories: stationary and non-stationary. Stationary penalty functions, use fixed penalty values through-out the minimization, while in contrast, in non-stationary penalty functions, the penalty values are dynamically modified. In the literature, results obtained using non-stationary penalty functions are almost always superior to those obtained through stationary functions[13].

A penalty function is, generally, defined as [13],

$$F(x) = f(x) + h(k)H(x) \quad (15)$$

where $f(x)$ is the objective function to be minimized of the constrained optimization problem as in (1); $h(k)$ is a dynamically modified penalty value, where k is the algorithm's current iteration number; and $H(x)$ is a penalty factor, defined as

$$H(x) = \sum_{i=1}^m \theta(q_i(x))q_i(x)^{\gamma(q_i(x))} \quad (16)$$

where $q_i(x) = \max\{0, g_i(x)\}$, $i = 1, \dots, m$. The function $q_i(x)$ is a relative violated function of the constraints; $\theta(q_i(x))$ is a multi-stage assignment function; $\gamma(q_i(x))$ is

the power of the penalty function; and $g_i(x)$ are the constraints described in (2). The functions $h(k)$, $\theta(q_i(x))$ and $q_i(x)$ are problem dependent and can be chosen after some trials [14] and [17] as will be indicated.

In this paper, a non-stationary multi-stage assignment penalty function is used.

5. Power Losses Optimization of SEIG Using CO-PSO

Using the proposed CO-PSO methodology to minimize the power losses in the SEIG can be described as:

- The objective function to be minimized, $f(x)$ is the power losses defined in (11) as a function of the capacitance X_c is used.
- The voltage is the constrained variable used, so (2) includes one variables ($m=1$)

$$V_T(x) \leq V_{desired}$$

6. Simulation Results

The proposed CO-PSO is tested for the SEIG shown in Fig. 1. Two different cases are used to test the capability of the proposed method, the first one is pure resistive load and the second one is R-L load. Comparisons between the proposed method and the conventional PSO are held.

The proposed CO-PSO technique is used to get the required capacitance for compensating SEIG with minimizing the power losses, keeping the terminal voltage at 1 p.u. with different loading conditions.

While PSO technique is used to get the required capacitance for compensating SEIG with minimizing the power losses, keeping the terminal voltage within certain limit.

The PSO's parameters used: $c_1 = c_2 = 2$; w was gradually decreased from 1.2 towards 0.1. Some variants of PSO impose a maximum value on the velocity, VV_{max} , to prevent the swarm from explosion. In this search VV_{max} was always fixed, to the value of $VV_{max} = 4$. The size of the swarm was set equal to 20 with 5 runs were performed, and both algorithms ran for 50 iterations, in each case. A violation tolerance was used for the constraints. Thus, a constraint $g_i(x)$ was assumed to be violated, only if $g_i(x) > 10^{-5}$.

Regarding the penalty parameters, the same values as the values reported in [13] were used to obtain these results. The penalty function parameters are:

- If $q_i(x) < 1$, then $\gamma(q_i(x)) = 1$,
otherwise $\gamma(q_i(x)) = 2$.
- $h(k) = k\sqrt{k+1}$
- Moreover, if $q_i(x) < 0.001$
then $\theta(q_i(x)) = 50$, else,
if $q_i(x) < 0.01$
then $\theta(q_i(x)) = 20$, else,
if $q_i(x) < 1$
then $\theta(q_i(x)) = 100$,
Otherwise $\theta(q_i(x)) = 250$

In the first case, the wind speed is varied from 0.7 to 1.1 p.u, with pure resistive load changes from 1 to 1.4 p.u. The exciting capacitance (X_c), required for excitation with minimum power losses at 1 p.u. terminal voltage is depicted in Table 1 with CPSO. Moreover the results obtained from conventional PSO for the first case are depicted in Table 2. From these tables, it is clear that there is a decrease in P_{losses} using modified PSO. Moreover the voltage in CPSO is set at 1 p.u. while in PSO the voltage is implemented in the system as a range of operations, the best range of voltages for the results in Table 2 is between 0.9 and 1.2 p.u.

Table 1 The exciting capacitance and the minimum at different loading conditions using proposed CO-PSO 1st Case

Speed V (p.u)		0.7	0.8	0.9	1	1.1
R _L (p.u)						
1	X _c (p.u)	0.9410	0.9925	1.0655	1.0965	1.1412
	P _{LOSS} (p.u) min	0.3443	0.3617	0.3875	0.3989	0.4159
1.1	X _c (p.u)	1.2477	1.3252	1.3227	1.3949	1.4838
	P _{LOSS} (p.u) min	0.3094	0.3203	0.3199	0.3301	0.3426
1.2	X _c (p.u)	1.1088	1.4857	0.9657	1.0332	1.1467
	P _{LOSS} (p.u) min	0.2057	0.1927	0.2198	0.2298	0.2360
1.3	X _c (p.u)	0.9457	1.0626	1.0914	1.0765	1.0615
	P _{LOSS} (p.u) min	0.2628	0.2803	0.2997 4	0.3041	0.3508
1.4	X _c (p.u)	1.5633	1.6344	1.0427	1.1182	1.2014
	P _{LOSS} (p.u) min	0.1985	0.2061	0.1585	0.1633	0.1689

Table 2 The exciting capacitance and the minimum losses at different loading conditions using PSO 1st case.

Speed V (p.u)		0.7	0.8	0.9	1	1.1
R _L (p.u)						
1	X _c (p.u)	0.76	0.802	0.841	0.8772	0.9117
	P _{LOSS} (p.u) min	0.2869	0.3014	0.3125	0.3217	0.3354
1.1	X _c (p.u)	0.84	0.89	0.933	0.9788	1.0229
	P _{LOSS} (p.u) min	0.2578	0.2669	0.2580	0.2662	0.2763
1.2	X _c (p.u)	0.91	0.96	1.015	1.071	1.1235
	P _{LOSS} (p.u) min	0.2285	0.2141	0.2176	0.2275	0.2337
1.3	X _c (p.u)	0.96	1.025	1.089	1.1523	1.214
	P _{LOSS} (p.u) min	0.1285	0.1829	0.1880	0.1944	0.2008
1.4	X _c (p.u)	1.012	1.085	1.1553	1.226	1.296
	P _{LOSS} (p.u) min	0.1563	0.1623	0.1651	0.1701	0.1759

Figs. 2 and 3 show the power losses in two selected cases at R_L= 1 and 1.3 p.u.

From these Figs., the losses in the CPSO is less than losses in PSO. Moreover the constant voltage of operation was achieved at 1 p.u .

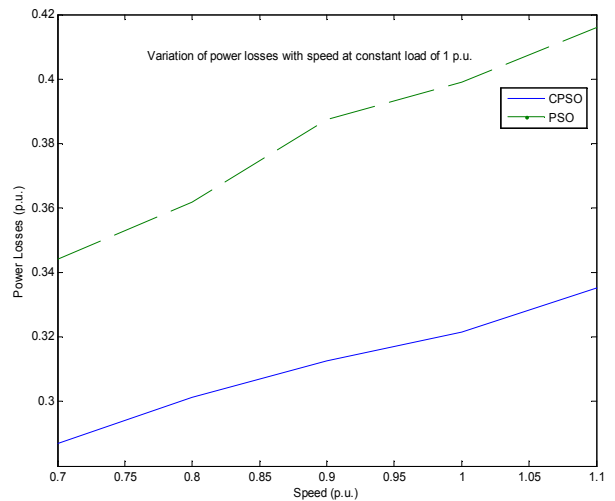


Fig.2, The variation of power losses with speed at constant R_L=1 p.u.

In the second case, R-L load is used with an impedance increased gradually from 0.8 to 2.4 p.u at constant power factor of 0.8, then the exciting capacitance (X_c), required for compensation at minimum power losses and 1 p.u terminal voltage is depicted in Table 3.

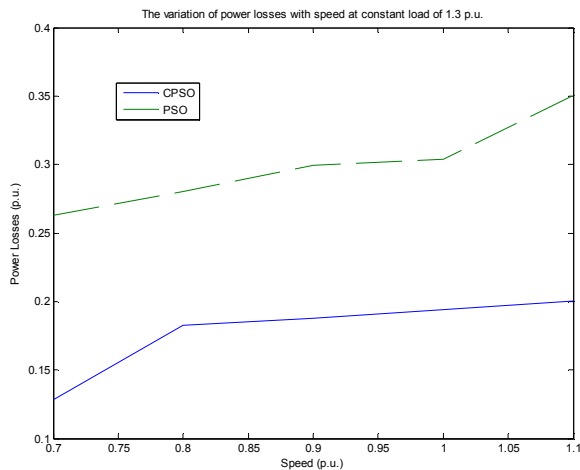


Fig.3, The variation of power losses with speed at constant $R_L=1.3$ p.u.

Table 3 The exciting capacitance and the minimum losses at different loading conditions using proposed CO-PSO 2nd case.

Z_L (p.u.) \ Speed V (p.u.)		0.7	0.8	0.9	1	1.1
0.8	X_c (p.u)	0.46	0.68	0.694	0.732	0.8117
	P_{LOSS} min (p.u)	0.421	0.43	0.468	0.562	0.579
1.2	X_c (p.u)	0.68	0.69	0.733	0.802	0.897
	P_{LOSS} min (p.u)	0.401	0.42	0.46	0.547	0.6
1.6	X_c (p.u)	0.732	0.78	0.802	0.843	0.867
	P_{LOSS} min (p.u)	0.394	0.40	0.428	0.487	0.521
2.0	X_c (p.u)	0.821	0.84	0.878	0.899	0.901
	P_{LOSS} min (p.u)	0.366	0.38	0.400	0.456	0.496
2.4	X_c (p.u)	0.893	0.90	0.911	0.932	0.942
	P_{LOSS} min (p.u)	0.288	0.32	0.366	0.402	0.422

Moreover the results obtained from conventional PSO for the second case are in Table 4. From these tables, it is clear that there is a decrease in P_{losses} using modified PSO. Moreover the voltage in CPSO is set at 1 p.u. while in PSO the voltage is implemented in the system as a range of operations. The best range of voltages for the results in Table 2 is between 0.85 and 1.25 p.u.

Figs. 4 and 5 show the power losses in two selected cases at impedance of $Z_L=1.2$ and 2.4 p.u.

From these Figs., the losses in the CPSO is less than losses in PSO, moreover the constant voltage of operation at 1 p.u. rather than operating ranger for voltage in PSO.

Table 4 The exciting capacitance and the minimum losses at different loading conditions using proposed PSO.

Z_L (p.u.) \ Speed V (p.u.)		0.7	0.8	0.9	1	1.1
0.8	X_c (p.u)	0.6665	0.6896	0.7760	0.9373	0.9665
	P_{LOSS} min (p.u)	0.4867	0.5029	0.5635	0.6766	0.6971
1.2	X_c (p.u)	0.7127	0.7179	0.9441	3.0585	3.7642
	P_{LOSS} min (p.u)	0.4812	0.5052	0.5654	0.6733	0.7
1.6	X_c (p.u)	0.8444	0.8531	0.8616	0.8168	0.7571
	P_{LOSS} min (p.u)	0.4728	0.4872	0.5307	0.6039	0.6460
2.0	X_c (p.u)	0.9014	0.8840	0.8476	0.8969	0.9045
	P_{LOSS} min (p.u)	0.4904	0.5213	0.3840	0.4378	0.4762
2.4	X_c (p.u)	0.9062	0.9220	0.9642	1.0017	1.0260
	P_{LOSS} min (p.u)	0.3456	0.3852	0.4538	0.4985	0.5233

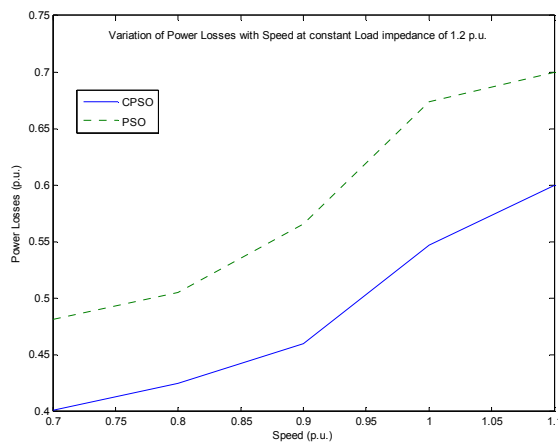


Fig.4, The variation of power losses with speed at constant $Z_L=1.2$ p.u.

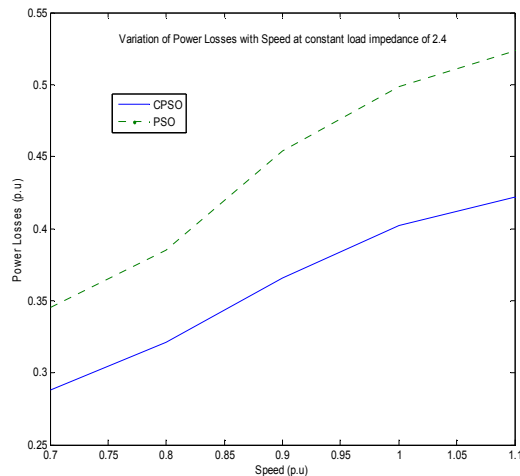


Fig.5, The variation of power losses with speed at constant $Z_L=2.4$ p.u.

7. Conclusions

This paper describe a steady state model for an induction machine in the generating mode, which has the feature of a nonlinear variation in the machine parameters that are dependent on the operating condition of the machine. The capability of the PSO method to address CO problem was investigated through the optimization and control of SEIG. Results obtained through the use of a non-stationary multi-stage penalty function, imply that PSO is a good alternative for tackling CO problems. It should be mentioned that the results are competitive as the inequality constrains changed into equality ones. The voltage will be held constant at the desired value not in certain limits by the selection of the appropriate capacitors to achieve minimization of the power losses with different loading conditions. Results show the supremacy of the proposed PSO over conventional PSO in the decreasing the power losses and operating voltage range.

Appendix

The data for Induction Generator used in this study are [2]: $R_s=0.1$ p.u.; $X_s=0.2$ p.u.; $R_r=0.06$ p.u.; $X_r=0.2$ p.u .

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