ANN Model for Estimation of Capacitance Requirements to Maintain Constant Air-Gap Voltage of Self-Excited Induction Generator with Variable Load

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Abstract
It is essential to supply electric power at rated voltage and frequency to the consumers for efficient and safe operation of electric equipment or other appliances under varying conditions of load connected in power system. The dependence of output voltage and frequency of Self-Excited Induction Generator (SEIG) on its speed, load and terminal capacitance poses limitations on its use in public sector utilities for power generation. In power systems, the utility of SEIG as stand alone machine has started gaining importance when power engineers encountered difficult situations for installation of transmission and distribution lines in the remote areas due to difficult geographical conditions. The probability of reduced terminal voltage at rated or near full load become more pronounced when power is supplied from an isolated generator. Thus, to keep the load voltages at rated level under vide range of load variations, it is necessary to regulate the terminal capacitance to generate constant air-gap voltage (E1 = 1.00 pu). In this paper an attempt is made to model the behavior of SEIG to maintain constant air-gap voltage using Artificial Neural Networks (ANN). The results are in good agreement with the analytical solution and are verified experimentally.

Keywords
Self-excited induction generator, artificial neural networks, terminal capacitance.

I. Introduction

The dependence of output voltage and frequency of self-excited induction generator on its speed, load and terminal capacitance poses limitations on its use in public sector utilities for power generation. To bring economic and social growth in hilly and under developed areas electric power is the basic requirement that forced the researchers to find an alternative sources of power generation from non-conventional energy sources. Self-excited induction generator (SEIG) as stand alone machine has emerged as substitute arrangement for power generation in hilly areas utilizing wind energy. Though SEIG has a number of advantages, but it suffers from inherent poor voltage regulation due to the difference between the reactive power supplied by the shunt capacitors and VARs required by the load and machine, when operated with fixed value of capacitance. The additional capacitance requirements cannot be determined without the knowledge of operating conditions and performance characteristics of the machine and its behavior under different terminal conditions. The design of thyrister phase controlled voltage regulators for optimum output voltage and voltage regulators using thyristor-controlled inductor for cost-effective voltage regulation at varying loads demonstrates the role of SEIG in power system to meet frequency sensitive loads requirements [1-3]. The alternative use of synchronous condenser to meet reactive power requirements that is costlier in maintenance and operation is also proposed [4]. Singh et al. [5] have developed an algorithm for calculating the number of capacitor steps required to generate voltage within the specified upper and lower limit for loading the machine up to its rated capacity. Ojo [6] concluded that SEIG with the long shunt connections has the tendency to operate at higher saturation level.

Insufficient capacitance does not allow the generator to build up and selection of larger value of capacitance at particular speed, invites transients due to sudden rise in voltage on removal of load. Bim et al. [7] have used the approximate analysis for long shunt SEIG to estimate the value of shunt and series capacitors. Researchers have examined the capacitance requirements and performance of self-excited induction machines by using the basic model having a single parallel capacitor for each phase of the machine [8 -9]. The single capacitor is ideal to provide the reactive power required for self-excitation when the generator supplies a constant ac load and is driven at a fixed mechanical shaft speed [10]. However, any changes in load or rotor speed will result in fluctuating output voltage and frequency unless a more elaborate excitation and control strategy is used [11]. For frequency regulation, it reveals from the investigations that the series capacitor helps to maintain output frequency with varying rotor speed to a limited extent [12]. The versatile features like universal function approximation ability to model non-linear and complex systems, learning and fault tolerance have resulted in widespread applications of ANNs in diverse fields [13-16]. In the proceeding sections, the estimation of terminal capacitance requirements to maintain constant air-gap voltage of SEIG using ANNs is demonstrated.

II. Analytical technique to solve equivalent circuit of SEIG

Low initial and maintenance cost, robust construction of induction generator has made the machine attractive for off-grid application. Under this mode of operation the reactive power is supplied from the capacitor bank connected across the load and the machine. As air gap voltage (E_1) of machine are function of saturated magnetizing reactance (X_m) and generated frequency (a), the equivalent circuit diagram is drawn with reference to rated frequency of machine thus making the resistance parameter of rotor / stator and load resistance as frequency sensitive elements. Per

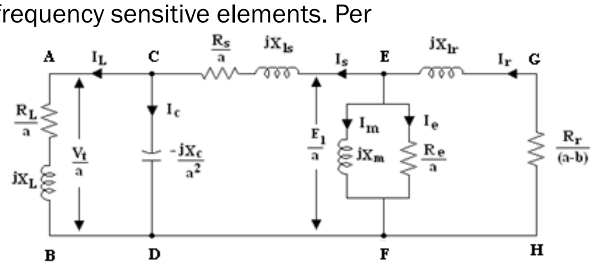

Fig. 1: Per phase equivalent circuit of self-excited induction generator

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phase conventional equivalent circuit of SEIG is shown in Fig. 1. The impedances of different branches seen from respective nodes are given below:

$$Z_{AB} = \left(\frac{R_L}{a} + jX_L\right) \qquad Z_{CD} = \frac{-jX_c}{a^2}$$

$$Z_{CE} = \left(\frac{R_s}{a} + jX_{ls}\right)$$

$$Z_{EF} = \left(\frac{R_e}{a} // jX_m\right) \qquad Z_{EH} = \left(\frac{R_r}{a-b} + jX_{lr}\right)$$

$$Z = (Z_{EH} // Z_{EF}) + Z_{CE} + (Z_{AB} // Z_{CD}) \tag{1}$$

The equivalent circuit results into a single loop equation:

$$I_S Z = 0$$

For successful voltage build up, Is ≠0

$$hence\ \ Z = 0 \tag{2}$$

By separating the real and imaginary components of equation (2) and putting separately equal to zero, two non-linear simultaneous equations are obtained in terms of machine parameters, speed, capacitive reactance, load resistance / reactance, magnetizing reactance (X_m) and generated frequency (a). Thus the equations obtained are as under:

$$F_O(X_m, a) = A_1 X_m a^5 + A_2 X_m a^4 + (A_3 X_m + A_4) a^3 + (A_5 X_m + A_6) a^2 + (A_7 X_m + A_8) a + A_9 X_m + A_{10} = 0 \quad ---(3) \tag{3}$$

$$G_O(X_m, a) = (B_1 X_m + B_2) a^4 + (B_3 X_m + B_4) a^3 + (B_5 X_m + B_6) a^2 + (B_7 X_m + B_8) a + B_9 = 0 \quad --- \tag{4}$$

The coefficients $(A_1 - A_{10})$ *and* $(B_1 - B_9)$ of two characteristics equations are obtained using 'Symbolic Mathematics' tool box in MATLAB and are given in Appendix –I. Polynomial equations (3) & (4) are solved with Newton-Raphson (NR) technique to determine the per unit value of saturated magnetizing reactance (X_m) and generated frequency (a). Per unit air-gap voltage (E_1) of SEIG is determined from its magnetic characteristics given in Appendix - II.

Now by solving the equivalent circuit of SEIG, the analysis of machine is simple and straight. Branch currents, terminal voltage and out-put power is computed as under:

$$I_r = \frac{-E_1/a}{R_r/(a-b) + jX_{lr}} \qquad I_m = \frac{E_1/a}{jX_m}$$

$$I_e = \frac{E_1/a}{R_e/a}$$

$$I_s = \frac{E1/a}{Z_{CE} + (Z_{CD} // Z_{AB})}$$

$$I_L = I_S \frac{-jX_C/a^2}{(R_L/a + j(X_L - X_C/a^2)}$$

$$I_S \frac{(R_L/a + jX_L)}{(R_L/a + j(X_L - X_C/a^2)} \qquad P_O = 3 I_L^2 R_L / a$$

$$V_t/a = E1/a - I_s(Rs/a + jX_{ls})$$

III. ANN model of self-excited induction generator

It is established that excitation phenomena of SEIG is greatly influenced by the excitation capacitance and speed. Similarly when induction generator operates in isolated mode its terminal voltage decreases due to the decrease in air-gap voltage due to armature reaction and demands more reactive power. Thus to maintain the terminal voltage of SEIG within the permissible operating limits, the air-gap voltage must be compensated by addition of reactive power supplied by the capacitor bank. Thus for varying load demand, the terminal capacitance has to be changed to new value (C_1= C±ΔC) to generate air-gap voltage (E_1 = 1.00). The proposed ANN model of SEIG is given in Fig. 2 that determines the excitation capacitance (C_1) required to maintain constant air-gap voltage E_1= 1.00 corresponding to magnetizing reactance (Xm_1). The determination of excitation capacitance to maintain constant air-gap voltage of SEIG by using ANN technique is described in the next section.

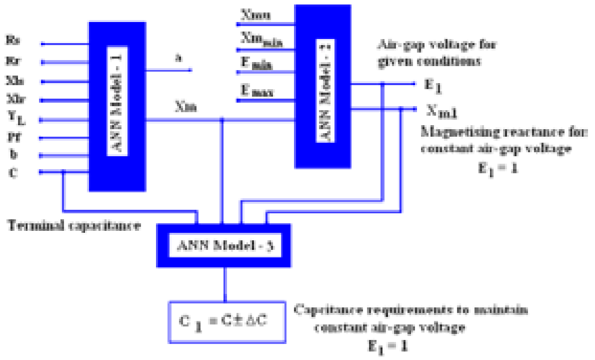

Fig. 2: ANN model of SEIG for maintaining constant air-gap voltage (E1 = 1.00)

A. Structure of ANN Model of SEIG

In this work, three models of ANN structure are used to achieve full mapping capability to determine the capacitance requirements to generate constant air-gap voltage under varying conditions of load. The structure of proposed ANN model of SEIG is described as under:

1. ANN Model

Is designed to have 8-11-2 architecture structure. Input layer has eight neurons accounting for input variables i.e. machine parameters (R_s, R_r, X_{ls}, X_{lr}), load admittance (Y_L), load power factor (Pf), speed (b) and capacitance (C). Single hidden layer has eleven neurons and the output layer has two neurons accounting for two output variables i.e. pu generated frequency (a) and magnetizing reactance (X_m).

2. Model

Is designed to have 5-7-2 architecture structure. Its input layer has five neurons accounting for five variables namely; un-saturated magnetizing reactance (X_{mu}), minimum value of magnetizing reactance (X_{min}), minimum and maximum value of air-gap voltage (E_{min} & E_{max}) and saturated magnetizing reactance (X_m) corresponding to given out-put of Model-I. Hidden layer has seven neurons and output layer has two neurons accounting for two variables i.e. air-gap voltage (E_1=1.00 pu) and saturated magnetizing reactance (X_{m1}) corresponding to constant air- gap voltage (E_1 = 1.00 pu).

3. ANN Model

Is designed to have 4-6-1 architecture structure. Input layer has four neurons accounting for four variables which are;

terminal capacitance (C), saturated magnetizing reactance (Xm) corresponding to given conditions of load, air-gap voltage (E_1=1.00 pu) and magnetizing reactance (X_{m1}) corresponding to constant air- gap voltage. Hidden layer has six neurons and output layer contains only one neuron accounting for output variable i.e. actual terminal capacitance (C_1= C±ΔC) required to generate constant air-gap voltage (E_1=1.00) for given loading conditions.

B. ANN training parameters

Widely used supervised neural network, the Multi-layer Perceptron (MLP) is used to train the network. The proposed ANN model of SEIG is trained with five thousand input-output training samples obtained from analytical technique using MATLAB programming corresponding to randomly chosen input variables as discussed in section II. The range of all input variables is carefully chosen which are compatible to real life applications of induction machine as self excited induction generator. The ANN structure of each model and training parameters are described in the Table 1. When sum-square error goal is achieved, the results of ANN network are tested with the validation input output samples which are other than the training samples. On achieving sufficient accuracy, the training process is terminated other wise network is trained further by setting new value of SEE goal.

Table 1: ANN architecture and training parameters.

MODEL	ANN Structure	Input Training Samples	Sum-square error goal	Initial Learning Rate	No of epochs
Model - I	8-11-2	5000	0.0075	0.01	8738
Model - II	5-7-2	5000	0.0006	0.01	6491
Model - III	4-6-1	5000	0.0005	0.01	2579

IV. Implementation of ANN model for estimation of capacitance

The proposed ANN model of SEIG is implemented to determine the capacitance requirements to maintain constant air-gap voltage under varying conditions of load at unity power factor. In this case the induction machine operation is carried with constant speed and load admittance at unity power factor is varied from 0.15 to 0.90 pu in eight steps. To investigate the performance of the proposed ANN model, input data is presented to Model-I with machine parameters and other conditions (speed = 1485 rpm and capacitance = 25.40 micro farad) and varying load admittance as mentioned above. Using trained ANN, the excitation capacitance requirements are computed with input data of machine parameters for speed of 1485 Rpm. The results obtained from the proposed ANN model for computation of excitation capacitance requirements to maintain constant air-gap voltage (E_1=1.00 pu) with varying load admittance are recorded in Table 2. Using the results of ANN model, the performance of SEIG with reference to terminal voltage and output power under constant air-gap voltage conditions is evaluated. Table 3 gives the comparison of results obtained from ANN model, analytical technique and experimental data of machine with varying load admittance.

The variation of magnetizing reactance and generated frequency corresponding to given conditions of varying load admittance from 0.15 to 0.90 pu, speed (1485 rpm) and capacitance (25.40 micro farad) is shown in Fig. 3. Excitation capacitance requirements (C_1=C±ΔC) to maintain constant air gap voltage (E_1 = 1.00) of SEIG corresponding to given speed (1485 rpm) with varying load is shown in Fig. 4. Generated frequency, output power, terminal voltage and branch currents of SEIG are evaluated using the results obtained from ANN model and the variations of these variables with

Table 2: Capacitance requirements to maintain constant air-gap voltage (E_1= 1.00 pu) with varying load admittance

Speed = 1485 Rpm			
Load Admittance at unity power factor (pu value)	Terminal capacitance required (C_1= C±ΔC) to maintain constant air-gap voltage (E_1 = 1.00)		
	Analytical Model	ANN Model	Experimental
0.2250	0.5806	0.5764	0.5902
0.4131	0.6327	0.6268	0.6519
0.5384	0.6771	0.6706	0.6880
0.5808	0.6939	0.6876	0.7197
0.6389	0.7184	0.7128	0.7438
0.8191	0.8064	0.8071	0.8326
0.8712	0.8353	0.8394	0.8552
0.9489	0.8815	0.8921	0.8958

Table 3: Terminal voltage and output power of SEIG with constant air-gap voltage (E_1=1.00)

Speed = 1485 Rpm with terminal capacitance (C_1= C±ΔC) as per Table 1.						
Load Admittance (pu)	Terminal Voltage (pu)			Output Power (pu)		
	Analytical Model	ANN Model	Experimental Model	Analytical Model	ANN Model	Experimental Model
0.2250	1.0170	1.0168	1.0289	0.6980	0.6978	0.7095
0.4131	0.9988	0.9989	1.0145	1.2362	1.2365	1.2498
0.5384	0.9874	0.9879	0.9976	1.5748	1.5763	1.6004
0.5808	0.9837	0.9843	0.9952	1.6862	1.6882	1.7106
0.6389	0.9787	0.9795	0.9928	1.8361	1.8390	1.8614
0.8191	0.9640	0.9655	0.9807	2.2835	2.2908	2.3082
0.8712	0.9599	0.9617	0.9663	2.4083	2.4172	2.4312
0.9489	0.9540	0.9560	0.9590	2.5906	2.6017	2.6109

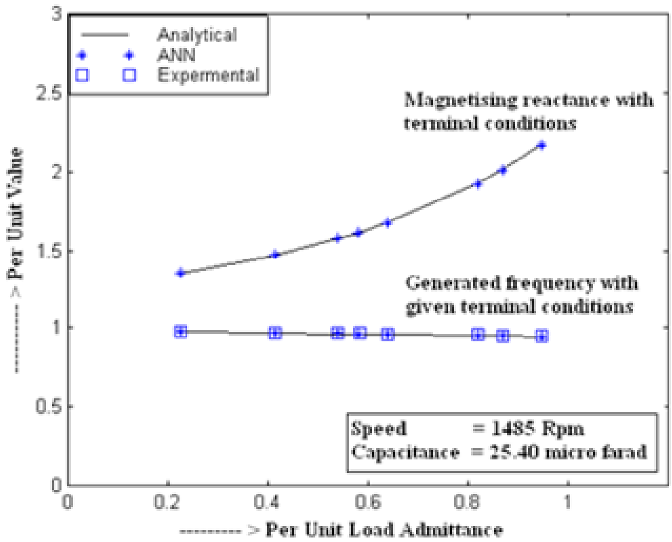

Fig. 3: Effect of load admittance on magnetizing reactance and generated frequency for given terminal conditions.

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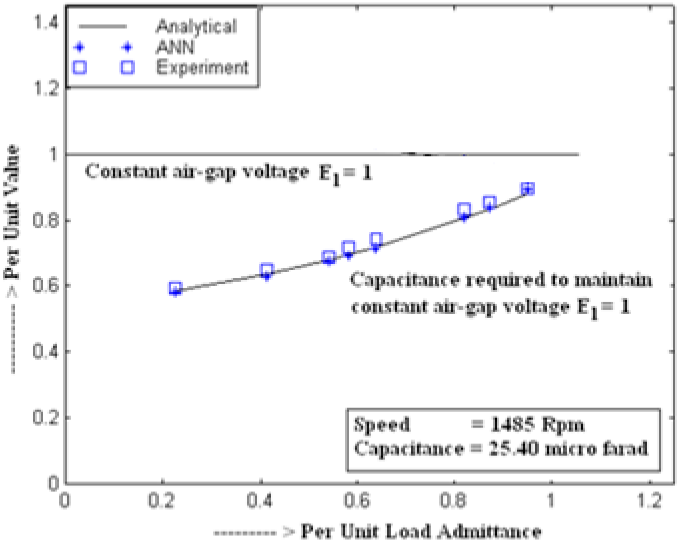

Fig. 4: Capacitance requirements to maintain constant air- gap voltage (E_1=1.00 pu) with varying load admittance

varying load admittance are verified experimentally. The closeness of results with experimental data as shown in fig. 3-6 validates the ANN model for analysis of SEIG for varying conditions of load.

V. Conclusions

The dependence of output voltage and frequency of SEIG on its speed, load and terminal capacitance poses limitations of its use as generator. The probability of reduced terminal voltage at rated or near full load are

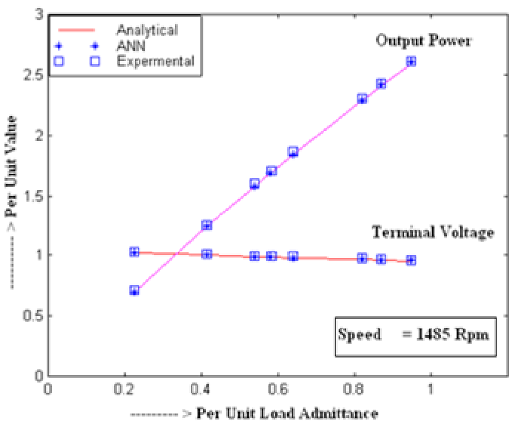

Fig. 5: Effect of load admittance on terminal voltage and output power with air-gap voltage (E_1= 1.00 pu)

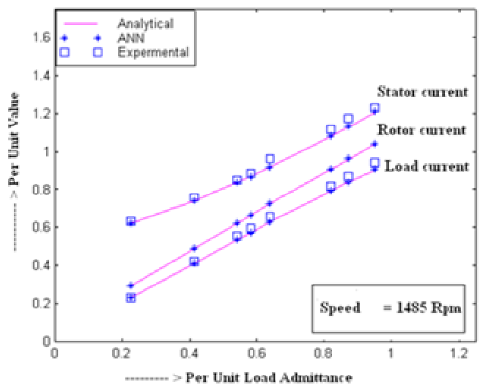

Fig.6: Effect of load admittance on stator / rotor & load current with constant air-gap voltage (E_1 =1.00 pu)

more pronounced when power is supplied from an isolated SEIG. Thus, to keep the load voltages at rated level under vide range of load variations, it is significant to regulate the exciting capacitance to generate constant air-gap voltage (E_1 = 1.00 pu). Using proposed ANN model, the capacitance requirements are evaluated under varying conditions of load at constant speed. The results obtained from ANN model are in good agreement with the analytical solution and are verified experimentally. It is observed that with the change in exciting capacitance to maintain air-gap voltage at E_1 = 1.0 pu, the voltage regulation of SEIG remains within the tolerable limits, thus enhancing the capability of machine to supply power at rated load voltage.

Appendix - I

Coefficients (A1 – A10) of equation $F_o(X_m, a)$

$$A_1 = -(X_{ls}X_{lr}X_L)$$
$$A_2 = (X_{ls}X_{lr}X_L)b$$
$$A_3 = X_{ls}(R_rR_L + R_eR_L + X_{lr}X_c) + X_{lr}(R_eR_L + X_cX_L + R_sR_L) + X_L(R_eR_r + R_sR_e + R_sR_r)$$
$$A_4 = X_{ls}R_e(X_{lr}R_L + R_rX_L) + R_eR_sX_{lr}X_L$$
$$A_5 = -X_{ls}(X_{lr}X_c + R_eR_L)b - X_{lr}(R_sR_L + R_eR_L + X_cX_L)b - (R_sR_eX_L)b$$
$$A_6 = -X_{lr}R_e(R_sX_L + X_{ls}R_L)b$$
$$A_7 = -X_cR_r(R_s + R_L) - X_cR_e(R_L + R_s + R_r)$$
$$A_8 = -R_eX_{lr}X_c(R_L + R_s) - R_eR_rX_c(X_L + X_{ls}) - R_eR_sR_rR_L$$
$$A_9 = R_eX_c(R_s + R_L)\,b$$
$$A_{10} = X_cX_{lr}R_e(R_L + R_s)\,b$$

Coefficients (B1 – B9) of equation $G_o(X_m, a)$

$$B_1 = X_{ls}X_L(R_e + R_r) + X_{ls}X_{lr}R_L + X_{lr}X_L(R_e + R_s)$$
$$B_2 = X_{ls}X_{lr}X_LR_e$$
$$B_3 = -X_{ls}(R_eX_L + X_{lr}R_L)b - X_{lr}X_L(R_s + R_e)b$$
$$B_4 = -(X_{ls}X_{lr}X_LR_e)b$$
$$B_5 = -X_cR_e(X_{ls} + X_{lr} + X_L) - R_LR_e(R_s + R_r) - R_L(X_{lr}X_c + R_sR_r) - X_c(R_sX_{lr} + X_{ls}R_r + X_LR_r)$$
$$B_6 = -R_eX_{lr}(X_{ls}X_c + X_cX_L + R_sR_L) - R_rR_e(X_{ls}R_L + R_sX_L)$$
$$B_7 = R_e(X_{lr}X_c + X_{ls}X_c + X_cX_L + R_sR_L)\,b + X_cX_{lr}(R_s + R_L)b$$
$$B_8 = R_eX_{lr}(X_{ls}X_c + X_cX_L)\,b + (X_{lr}R_eR_sR_L)b$$
$$B_9 = R_eX_cR_r(R_L + R_s)$$

Appendix – II

Machine specifications and its parameters:

V_{base} = 415 Volts	$Z_{base} = V_{base}/I_{base}$
I_{base} = 4.33 Amp	Z_{base} = 95.84 ohm
$P_{base} = V_{base}I_{base}$	$Y_{base} = 1/Z_{base}$
P_{base} = 1797 VA	Y_{base} = 0.0104 mho

$N_{base} = 1500\ RPM \qquad C_{base} = 33.21\ mF$

$F_{base} = 50\ Hz$

Machine parameters in ohms:

$$R_S = 5.76\ ohm \qquad X_{ls} = 9.37\ ohm$$

$$R_r = 4.19\ ohm \qquad X_{lr} = 9.37\ ohm$$

$$R_e = 3118\ ohm \qquad X_{mu} = 285\ ohm$$

Magnetizing characteristics of machine
(pu values):

$X_m < 2.6930$	$E_1 = 1.3818 - 0.2117X_m$
$X_m < 2.8386\ \&\ X_m >= 2.6930$	$E_1 = 2.1697 - 0.5057X_m$
$X_m < 2.9716\ \&\ X_m >= 2.8386$	$E_1 = 3.8732 - 1.1057X_m$
$X_m > 2.9716$	$E_1 = 0$

References

[1] A. E. Hammad, R. M. Mathur, "New generalized concept for the design of thyristor phase controlled var compensator", IEEE Trans. Power Apparatus Systems, vol. 98, pp 219–231, 1979.

[2] H. Frank, B. Landstorm, "Power factor correction with thyristor controlled capacitors", Asea Jounal, vol. 44, pp 180–184, 1971.

[3] M. B. Brennen, A. Abbandanti, "Static exciters for induction generators", IEEE Trans. Industrial Applications, vol.13 (5), pp 422–428, 1977.

[4] B.T Ooi, R. A. David, "Induction generator / synchronous condenser system for wind turbine power, IEE Proceeding, vol. 126 (1), pp 69–74, 1979.

[5] S. P. Singh, B. Singh, M. P. Jain,"Performance characteristics and optimum utilization of a cage machine as capacitor excited induction generator", IEEE Trans. Energy Conversion, vol. 5 (4), pp 679–684,1990.

[6] O. Ojo, "Performance of self excited single-phase induction generators with short shunt and long shunt excitation connections", IEEE Trans. Energy Conversion, vol. 11 (3), pp 477–482, 1996.

[7] E. Bim, J. Szajner, Y. Burian,"Voltage compensation of an induction generator with long shunt connection", IEEE Trans. Energy Conversion, vol. 10 (3), pp 305–313, 1995.

[8] S. S. Murthy, "A novel self-excited self-regulated single-phase induction generator", Part 1: Basic system and theory, IEEE Transactions on Energy Conversion, vol. 8, (3), pp. 377-382, 1993.

[9] D. Sutanto, C. Grantham, M. F. Rahman, "Regulated self-excited induction generator for use in a remote area power supply", Sixth International Conference on Electrical Machines and Drives, pp 234-239, 1993.

[10] L. Wang, J. Su,"Dynamic performances of an isolated self-excited induction generator under various loading conditions", IEEE Transactions on Energy Conversion, vol.14(1), pp.93-100, 1999.

[11] D. Seyoum, C. Grantham, M. F. Rahman,"The dynamic characteristics of an isolated self-excited induction generator driven by a wind turbine," IEEE Transactions on Industry Applications, vol.39(4), pp.936-944, 2003.

[12] E. Muljadi, J. Sallan, M. Sanz, C.P. Butler Eld," Investigation of self-excited induction generators for wind turbine applications", Conference Record of the 1999 IEEE Thirty-Fourth IAS Annual Meeting, Industry Applications Conference, vol.1, pp.509-515, 1999.

[13] Narendra K. S, K. Parthasarathy, "Identification and control of dynamical systems using neural networks," IEEE Transactions on Neural Networks, vol.1, pp. 24-27,1990.

[14] S. Limanond, J. Si, "Neural network based control design: An LMI approach, "IEEE Transactions on Neural Networks, vol. 9(6), pp. 1422-1429, 1998.

[15] Ashok K. Goel, S.C. Saxena, S. Bhanot, "Fast learning algorithm for training feed-forward neural networks", International Journal of System Science, vol. 37, no. 10, pp. 709-722, 2006.

[16] S. Jagannathan, "Discrete-time CMAC NN control of feedback linearizable non-linear systems under a persistence of excitation", IEEE Transactions on Neural Networks, vol. 10(1), pp 128-137, 1999.

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