Excitation Control of Self Excited Induction Generator using Genetic Algorithm and Artificial Neural Network

Dheeraj Joshi, K S Sandhu

Abstract**—** Induction generators which may be operated in grid or self-excited mode, are found to be successful machines for wind energy conversion. Out of these two self-excited mode is gaining importance due to its ability to convert the wind energy into electrical energy for large variations in operating speed. However it has been found that these machine exhibits a poor voltage regulation. Steady-state analysis of self excited induction generator reveals that such generators are not capable to maintain the terminal voltage and frequency in the absence of expensive controllers. In turn addition of such controllers may result into a fall in popularity of this machine due to its simplicity. Another simple way to control the terminal voltage is through excitation control using series compensation. In this paper artificial intelligent techniques are used to model the control strategy for proper reactive compensation under different operating conditions. Genetic algorithm along with artificial neural network has been proposed to estimate the values of shunt and series excitation capacitance to maintain the terminal and load voltage. Simulated results as found using proposed control technique are verified using experimental results on a test machine. Simulated results are found to be in close agreement with experimental results.

Keywords**—** *Artificial Neural Network, Genetic Algorithm, Optimization, Self Excited Induction Generator, Wind Energy Generation.*

NOMENCLATURE

a per unit frequency

b per unit speed

C_{sh} shunt excitation capacitance per phase

C_{se} series excitation capacitance per phase

E_1 air gap voltage per phase at rated frequency

f rated frequency

I_1 stator current per phase

I_2 rotor current per phase, referred to stator

I_r load current per phase

I_m magnetizing current per phase

R load resistance per phase

R_1 stator resistance per phase

R_2 rotor resistance per phase, referred to stator

V load voltage per phase

V_t terminal voltage per phase

X_1 stator reactance per phase

X_2 rotor reactance per phase, referred to stator

X_{sh} capacitive reactance due to C_{sh} at rated frequency

X_{se} capacitive reactance due to C_{se} at rated frequency

X_m magnetizing reactance per phase at rated frequency

Dheeraj Joshi is Senior Lecturer in Electrical Engineering Department of National Institute of Technology, Kurukshetra, Haryana-136119,India (phone: +91-1744-239656;fax:+91-1744-238050;email:dheeraj_joshi@rediffmail.com).

K.S.Sandhu is Professor in Electrical Engineering Department of National Institute of Technology, Kurukshetra, Haryana-136119,India (phone: +91-1744-238001; fax: +91-1744-238050; e-mail: kjssandhu@yahoo.com).

I. INTRODUCTION

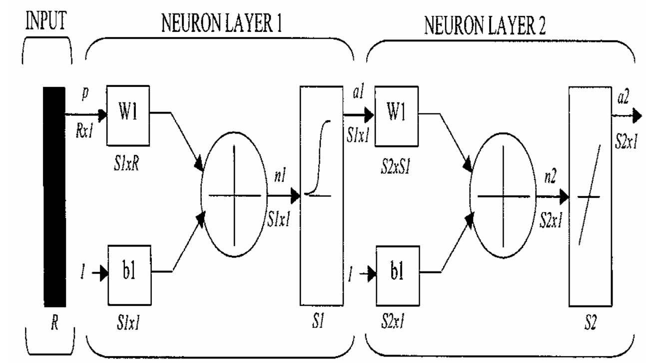
Most of the electrical power generation across the world is due to the use of fossil fuel, which are limited in reserve. These may vanish from earth if continued to be used at the same pace. A rapid depletion of fossil fuels as well as a fast growing power demand has pressurized the scientists to think about non conventional sources of energy such as wind energy, solar energy, tidal energy, etc. Use of such sources may be helpful to retain our resources of fossil fuel for some additional years. Scientists have observed that out of all potential non conventional sources wind energy seems to be more attractive and viable. It is observed that winds carry enormous amount of energy and the regions in which strong winds prevail for a sufficient time during the year may use it for electrical energy generation. In addition to this wind energy generation provides a clean and pollution free environment and does not lead to global warming. Further a wind turbine generator may be a worthwhile proposition for an isolated remote area due to absence of power grid. There are many considerations in the choice of generators for the wind turbine applications and several views prevail. However most of the researchers are in the favour of induction generators in self-excited mode due to its ability to convert mechanical power over a wide range of rotor speeds. Induction generators are also preferred due to several other advantages such as low cost, less maintenance and easy operation. The self-excited induction generators (SEIG) are also found suitable for few other applications such as tidal and mini hydroelectric energy conversion. Operation of induction generator in self-excited mode is useful under variable speed operation especially when wind speed is fluctuating within a wide range. Therefore it becomes the duty of researchers to investigate the behaviour of specific problem related issues of SEIG. To compute the steady state performance of SEIG, researchers adopted different models [1-12]. Main observation which was pointed out in case of self-excited induction generator is its poor voltage regulation. Various regulating schemes were proposed by research persons [13-25] to overcome this issue. However it has been realized that such schemes makes the system complicated and expensive. Reference [26] found the series compensation a simple and cheap alternative to such schemes. Many research scholars [27-31] studied the effects of series compensation using different techniques. It has been observed that during the analysis the degree of polynomial equation in unknown frequency increases due to the presence of series capacitor.

In this paper GA has been proposed to estimate the generated frequency, shunt and series capacitance for different operating speeds and with different load conditions. A control strategy using GA and ANN controller is proposed to control the terminal and load voltage of SEIG. Simulated results have been verified using experimental observation on a test machine.

II. Artificial Intelligent Techniques

A. Artificial Neural Networks

Artificial neural networks (ANN)[32-34], also called parallel distributed processing systems and connectionist, are generally used for function approximation, nonlinear modeling, system identification, pattern association, pattern classification etc. Fig. 1 gives the ANN architecture.



RR= Number of elements in Input

S1=Number of neurons in layer 1

S2= Number of neurons in layer 2

Fig. 1. Structure of Artificial Neural Network.

This network has a natural tendency for storing experimental knowledge and making it available for use. This architecture will not completely be constrained by the problem to be solved. The number of input and output neurons depend on the given problem but the number of hidden layers and associated neurons will depend on the designer. In this paper, the two-layer back propagation feed forward neural network has been used. A total of 5 neurons in hidden layer, two neuron in input layer and two neuron in output layer have been used. The network is set with ‘logsig’ activation function at the middle layer and ‘purelin’ activation function at the output layer. Levenberg-Marquadrt method has been adopted for supervised learning. Experimental data for test machine-1(see Appendix I) and computed data from GA have been used for training purpose.

B. Genetic Algorithm

Over the past few years, many researchers have been paying attention to real-coded evolutionary algorithms, particularly for solving real-world optimization problems. Genetic Algorithm (GA) [35] is one of them. Since the performance variables evaluation (a ,C_{sh} and C_{se}) in SEIG may take any real number, therefore, in this paper a real-coded genetic algorithm has been used to investigate the performance. In a real-coded GA, variables are coded in real numbers itself [36]. GA operators are directly applied on the real numbers (a

,C_{sh} and C_{se}) Three main operators responsible for the working of the GAs are reproduction, crossover, and mutation. Reproduction operator allows highly productive strings to live and reproduce, where the productivity of an individual is defined as a string's non-negative objective function value. There are many ways to achieve effective reproduction. Here, tournament selection is used instead of roulette-wheel selection, which is generally used. Higher values of tournament size give higher selection pressure, making the convergence faster. The second operator, crossover, exchanges genetic information. The study reveals that a number of crossover operators such as blend crossover (BLX), simulated binary crossover (SBX), unimodal normal distribution crossover (UNDX), simplex crossover (SPX) are commonly used. A detailed study of such operators can be found in [37-40]. Here parent centric recombination operator (PCX) has been used, as this operator assigns more probability for an offspring to remain closer to the parents than away from parents. The search power of this crossover is better than the simple crossover i.e. local or broader search can be done. Different mutation operators are used based on the coding of the variable. Since continuous variables are coded directly, the algorithm is flexible in nature. As PCX and the real-coded mutation operators have been used to have a search power similar to their counterparts, the overall algorithm performs better than the binary-coded GAs. Modified GA [35] processes fast convergence in comparison to conventional GA as reported in [41].

III. MODELING FOR STEADY STATE ANALYSIS

The steady-state operation of the self-excited generator with series and shunt capacitors may be analyzed by using the equivalent circuit representation as shown in Fig. 2.

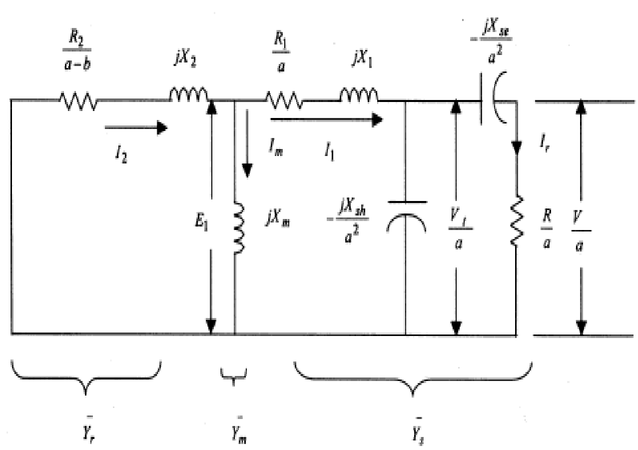


Fig. 2. Per phase equivalent circuit representation for two-capacitor self-excited induction generator.

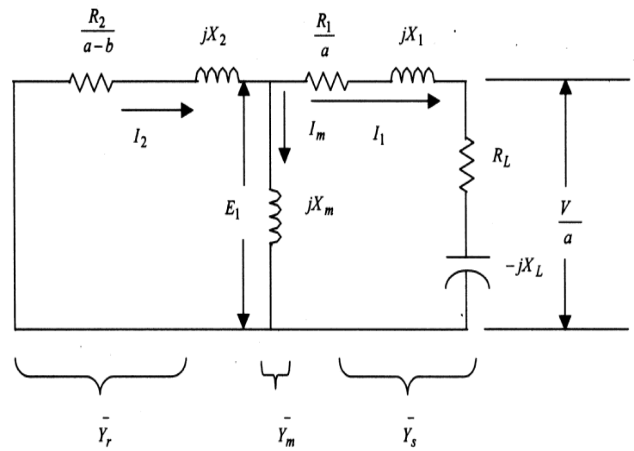


Fig 3. Per phase modified equivalent circuit representation.

In this circuit model all parameters are assumed to be independent of saturation except for magnetizing reactance. The core losses have been ignored. The network above can be further transformed into Fig. 3.

Where,

$$R_L = \frac{RX_{sh}^2}{a\left(a^2R^2 + \left(X_{sh} + X_{se}\right)^2\right)}$$

and

$$X_L = \frac{X_{sh}X_{se}\left(X_{sh} + X_{se}\right) + a^2R^2X_{sh}}{a^2\left(a^2R^2 + \left(X_{sh} + X_{se}\right)^2\right)}$$

As Fig.3 does not contain any e.m.f. or current source, therefore for successful generator operation, nodal analysis results into;

$$Y = \bar{Y}_s + \bar{Y}_m + \bar{Y}_r = 0 \tag{1}$$

$$Y_m = -j\frac{1}{X_m}$$

$$Y_s = \frac{R_L + \frac{R_1}{a}}{(X_1 - X_L)^2 + \left(R_L + \frac{R_1}{a}\right)^2} - j\frac{(X_1 - X_L)}{(X_1 - X_L)^2 + \left(R_L + \frac{R_1}{a}\right)^2}$$

$$Y_r = \frac{\frac{R_2}{a-b}}{X_2^2 + \left(\frac{R_2}{a-b}\right)^2} - j\frac{X_2}{X_2^2 + \left(\frac{R_2}{a-b}\right)^2}$$

Or

$Y=Y_R+jY_I$ (2)

Where,

Y_R= Real part of Y; Y_I= Imaginary part of Y.

For generator operation (1) and (2) are to be satisfied for unknown values of generated frequency '*a*' and magnetizing reactance 'X_m'. '*a*' may be evaluated by minimizing the real part of (2) and 'X_m' magnetizing reactance to be estimated using imaginary part of this equation.

A. Selection of C_{sh} at No Load

GA has been used to find the shunt capacitance at different speeds to maintain the rated voltage across the stator terminals at no load. The fitness function (*FF*) used here is,

$FF=Y_{rr}+V_{terr};$ (3)

Where

$Y_{RR}=Y_R * Y_R$; $V_{terr}=(1.0-V_t pu) * (1.0-V_t pu)$;

The value of R is ∞ and X_{se}=0 for computation of Y_R.

The first part of the fitness function has been used to find the generated frequency '*a*' and second part is used to maintain the voltage quality. Application of GA through (1) to (3) results into the computation of shunt excitation capacitance requirement at no load to maintain the rated voltage at a given operating speed. Such results may be used to establish the relation between operating speeds and shunt excitation capacitance. Fig. 4 shows the variation of shunt capacitance with speed for machine-I (see Appendix I) to maintain the terminal voltage as 1.0 pu at no load. It is observed reactive VARs requirement decreases with an increase in operating speed.

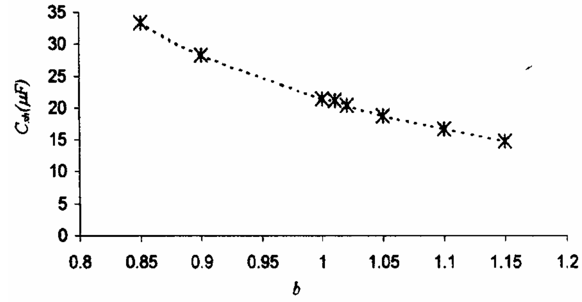


Fig. 4. Variation of shunt excitation capacitance with speed.

Curve in Fig.4 may be represented mathematically using MATLAB as;

$$C_{sh} = 21.44b^{-2.6808}$$

Thus any variation in speed may be accommodated by proper control of shunt excitation capacitance through GA controller as shown in Fig. 5.

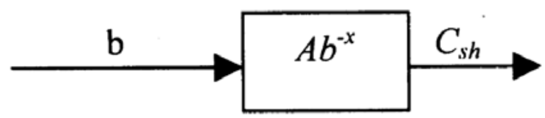


Fig. 5. GA Controller for variable speed operation.

Constants A and x are dependent upon machine parameters.

B. Selection of a and C_{se} Under Loaded Condition

For given value of operating speed and shunt capacitance as calculated above, GA may be used to find the optimum values of generated frequency, *a* and series capacitance C_{se} for a given load impedance and corresponding to operating speed. The *FF* used here is;

$FF=Y_{rr}+V_{err}+I_{1err};$

Where $Y_{RR}=Y_R * Y_R$ and Y_R has been computed for a given load resistance '*R*'.

$V_{err}=(1.0-Vpu) * (1.0-Vpu)$; $I_{1err}=(1.0-I_1 pu) * (1.0-I_1 pu)$

This fitness function is useful to control the voltage and stator current of SEIG.

This will lead to the estimation of 'a' and 'C_{se}' through GA for constant voltage for any operating speed 'b' and load resistance 'R'.

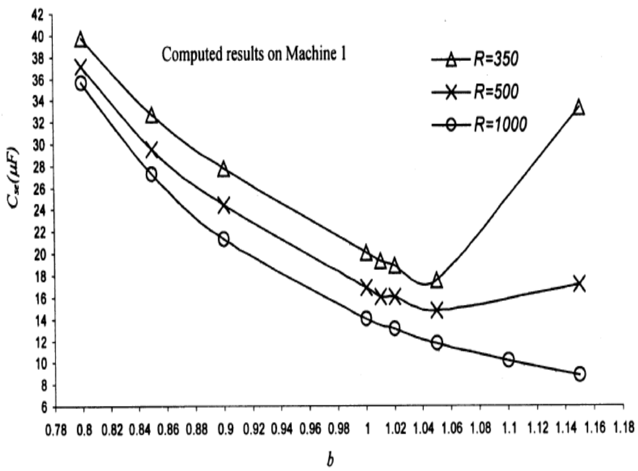


Fig. 6. Variation of series capacitance with speed at different loads for constant load voltage.

Fig. 6 shows the variation of computed values of C_{se} with operating speed for different values of load resistance. It is observed that with an increase in speed, initially the value of series capacitance C_{se} decreases and after attaining a minimum value it starts increasing. These characteristics are also useful to determine the operating speed for any load resulting in to minimum series capacitance with desired voltage regulation. Simultaneous variation of generated frequency with operating speed has been shown in Fig. 7.

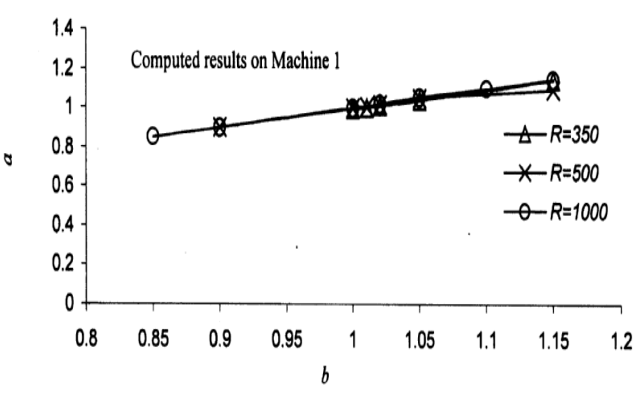


Fig. 7. Variation of generated frequency with speed at different loads for constant load voltage.

Variation of 'C_{se}' and 'a' as shown in Fig. 6 and Fig. 7 may be represented mathematically using MATLAB as shown in Appendix-II for machine-1.

ANN which is faster than GA may be used to compute the series capacitance for any value of load across machine terminals. In order to achieve constant voltage operation, training data as used for ANN is computed using expressions as given in appendix-II. In addition some experimental data at random may be fed and this has been incorporated in the present paper.

IV. PROPOSED CONTROL STRATEGY

Fig. 8 shows the control strategy to achieve constant voltage operation for SEIG for any operating speed and loading condition. GA controller has been modeled to decide the appropriate value of shunt excitation for any speed under no load conditions. ANN controller is used to compute the unknown frequency and series capacitance in such a way that it results in constant voltage operation without exceeding the rated current for induction generator.

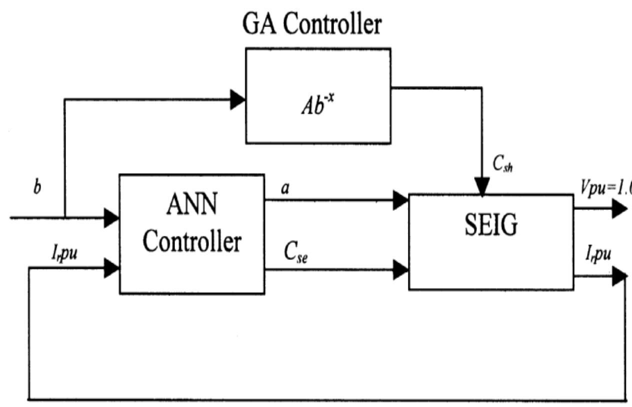


Fig. 8. Constant voltage SEIG model.

V. RESULTS AND DISCUSSIONS

Table I shows the comparison of simulated results using proposed control strategy and experimental results on machine-1. A close agreement between the two proves the validity of model proposed. Table II shows the computed results on machine 1 using ANN and GA for different operating speed and load current. GA has been used to compute the shunt excitation capacitance. ANN is employed to estimate the series capacitance and unknown generated frequency corresponding to given operating speed and load current. It is observed that there is a need of simultaneous control of shunt and series capacitance to achieve a constant voltage operation without exceeding the thermal limits (to be decided by stator current). Constant voltage variable frequency operation as given by proposed modeling may be useful for frequency insensitive loads such as heating etc. in remote and windy areas. Further it has been observed that rated value of generated frequency is possible only and only if operating speed is maintained slightly above rated speed.

TABLE I EXPERIMENTAL VERIFICATION OF PROPOSED MODEL

S. No.	Experimental Results						Simulated Results			
	b	$I_t pu$	C_{sh} (μF)	C_{se} (μF)	a	Vpu	C_{sh} (μF)	C_{se} (μF)	a	Vpu
1	1.050	0.331578	19.70	19.70	1.0260	1.000789	18.82	18.56	1.0322	1.000341
2	1.028	0.289473	19.70	18.86	1.0272	1.002368	19.92	20.65	1.0136	0.990286
3	1.040	0.257894	19.70	15.60	1.0264	0.999473	19.32	16.60	1.0244	0.984412
4	1.032	0.231578	19.70	15.60	1.0254	1.001578	19.92	15.81	1.0162	0.988255

TABLE II SIMULATED RESULTS ON SEIG.

S.No.	b	$I_t pu$	a	C_{se} (μF)	C_{sh} (μF)	$I_l pu$	Vpu	$V_l pu$
			ANN Results		GA Results			
1.	1.00	0.261462	0.990257	16.91916	21.44700	0.969900	0.996726	1.085672
2.	1.00	0.235402	0.986963	16.58715	21.44700	0.925175	0.978962	1.05623
3.	1.00	0.281894	0.990267	17.93495	21.44700	0.988846	1.001347	1.092839
4.	1.02	0.272224	1.00622	19.50613	20.33814	0.921699	0.990581	1.061863
5.	1.02	0.239534	1.009549	16.2258	20.33814	0.917277	0.996146	1.074680
6.	0.90	0.207347	0.88405	24.08194	28.44679	0.964466	0.93415	0.971997
7.	0.90	0.138953	0.890797	25.25766	28.44679	0.932968	0.963103	0.978047

VI. CONCLUSION

Induction generators have gained a lot of attention due to their applications in wind energy conversion systems. These may be operated in grid or self-excited mode. Self-excited induction generators are found to be most suitable for wind energy conversion in remote and windy locations. Such generators seem to be very attractive in case terminal and load voltages are controllable from no load to full load operation. In this paper a control technique based on GA and ANN has been proposed to achieve the constant voltage operation for SEIG. Proposed scheme results into the appropriate selection of shunt and series capacitors for any operating speed and load. Terminal and load voltage maintained near to the rated value without exceeding the rated current of induction generator.

APPENDIX-I

MACHINE-1

- Specifications

3-phase, 4-pole, 50 Hz, star connected, squirrel cage induction machine
750W/1HP, 380 V, 1.9 A

- Parameters

The equivalent circuit parameters for the machine in pu are

$R_1 = 0.0823, R_2 = 0.0696, X_1 = X_2 = 0.0766$

- Base values

Base voltage =219.3 V
Base current =1.9 A
Base Impedance=115.4 Ω
Base frequency=50 Hz
Base speed=1500rpm

- Air gap voltage

The variation of magnetizing reactance with air gap voltage at rated frequency for the induction machine is as given below.

$$\begin{array}{ll} X_m < 169.2 & E_1 = 512.69 - 2.13X_m \\ 179.42 > X_m \ge 169.2 & E_1 = 891.66 - 4.37X_m \\ 184.46 > X_m \ge 179.42 & E_1 = 785.79 - 3.78X_m \\ X_m \ge 184.46 & E_1 = 0 \end{array}$$

APPENDIX-II

For R =350,following relationships are found;

$$C_{se} = \begin{cases} -74.64b + 94.636 & 1.0 \le b < 1.01 \\ -45.019b + 64.719 & 1.01 \le b < 1.02 \\ -44.447b + 64.136 & 1.02 \le b < 1.05 \\ 156.94b - 147.32 & 1.05 \le b < 1.15 \end{cases}$$

$$a = 0.3797e^{0.9545b}$$

For R =500,following relationships are found;

$$C_{se} = \begin{cases} -76.01b + 92.78 & 0.9 \le b < 1.01 \\ -32.038b + 48.364 & 1.01 \le b < 1.05 \\ 23.589b - 10.045 & 1.05 \le b < 1.15 \end{cases}$$

$$a = -1.3625b^2 + 3.5654b - 1.2073$$

For R =1000,following relationships are found;

$$C_{se} = 705.24b^4 - 3284.2b^3 + 5784b^2 - 4587.3b + 1396.3$$
$$0.85 \le b < 1.15$$

$$a = 0.9973b^{0.9871}$$

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BIOGRAPHIES

Dheeraj Joshi was born in Kota, Rajasthan, India on 11th July 1978. He received B.E. (Electrical) degree from University of Rajasthan, Jaipur, India, in 1998 and M.E. (Power Apparatus and Electric Drives) degree from Indian Institute of Technology, Roorkee (Formerly University of Roorkee, Roorkee, India), in 2000. He joined Electrical Engineering Department, National Institute of Technology, Kurukshetra (Formerly Regional Engineering College, Kurukshetra) in September 2001. Currently, he is Senior Lecturer in the same institute. His areas of interest are self-excited induction generators, artificial intelligence, power electronics and electric drives. He is a Life Member of the Indian Society of Technical Education.

Kanwarjit Singh Sandhu was born in Haryana, India on 21 December 1957. He received the B.Sc. Engg. (Electrical), M. Sc. (Power System) and Ph.D (Electrical Machines) degrees from Regional Engineering College, Kurukshetra University, Kurukshetra, India in 1981, 1985 and 2001, respectively. He joined the Electrical Engineering Department of Regional Engineering College, Kurukshetra, as Lecturer in January 1983. Currently, he is Professor in Electrical Engineering Department, National Institute of Technology, Kurukshetra (Formerly Regional Engineering College, Kurukshetra), India. He has many international publications in the area of Electrical Machines & Induction Generators. His areas of interest include electrical machines, wind energy conversion, power quality, artificial intelligence and power systems.