Performance Analysis of Self-Excited Induction Generator Using Artificial Neural Network

D. Joshi, K. S. Sandhu, and M. K. Soni

Abstract—**Self-excited induction machines seem to be the most suitable generators for wind energy conversion in remote and windy areas. Steady state analysis for such machines is essential to estimate the behavior under actual operating conditions. This paper presents a new technique for the steady-state analysis of a three-phase self-excited induction generator feeding balanced unity power factor load. Iterative technique has been used to find the generated frequency and Artificial Neural Network (ANN) has been applied to capture the nonlinear magnetization characteristics of induction machine in place of piecewise linear approximation as used by other research persons. The results have been compared with experimental results. The comparison confirms the validity and accuracy of the ANN based modeling of induction generator.**

Index Terms—**Artificial neural network, magnetization characteristics, self-excited induction generator.**

NOMENCLATURE

a	per unit frequency
b	per unit speed
C	excitation capacitance per phase, μF
E_1	air gap voltage per phase at rated frequency, V
f	rated frequency, Hz
I_1	stator current per phase, A
I_2	rotor current per phase, referred to stator, A
I_C	capacitor current per phase, A
I_m	magnetizing current per phase, A
I_L	load current per phase, A
P_{out}	output power, W
R	load resistance per phase, Ω
R_1	stator resistance per phase, Ω
R_2	rotor resistance per phase, referred to stator, Ω
s	slip, $(a-b)/a$
V	terminal voltage per phase, V
X_1	stator reactance per phase, Ω
X_2	rotor reactance per phase, referred to stator, Ω
X_c	capacitive reactance due to C at rated frequency, Ω
X_m	magnetizing reactance per phase at rated frequency, Ω

I. INTRODUCTION

THE SELF-EXCITED induction generators (SEIG) have been found suitable for many applications such as wind, tidal, and small hydroelectric energy conversion in the past few years. Such generators may be used for lighting or cooking purpose to minimize the requirement of conventional fuels or firewood in the villages without high power quality of electrical energy. SEIG has many advantages such as brushless construction (squirrel-cage rotor), reduced size, absence of DC power supply for excitation as in synchronous generators, reduced maintenance cost, good overspeed capability, self short-circuit protection capability and no synchronizing problem.

A proper circuit representation and accurate mathematical modeling is essential to evaluate the steady-state performance of a SEIG for different operating conditions. To estimate and analyze the performance of a SEIG, researchers have made use of the conventional equivalent circuit of an induction motor. Some researchers [1]-[7] used the impedance model, and a few [8]-[11] used the admittance-based model for such computations. It is found that most of the researchers used the modeling, which results in a single polynomial equation of higher order in unknown generated frequency and magnetizing reactance. Therefore suitable techniques are required to compute the unknown variables. However, [10]-[11] suggested a new equivalent circuit model representation, which includes an active power source. In [9], iterative technique is applied to obtain the generated frequency of self-excited induction generator.

Irrespective of representations, it is essential to develop a mathematical modeling for nonlinear magnetization characteristics of induction machine. Such modeling is helpful to compute terminal voltage, in case unknown magnetizing reactance has been estimated. Most of the researchers employed experimental results to obtain the mathematical modeling of magnetization curve by using piecewise linear approximation to estimate the performance of SEIG [1]-[18]. However, artificial neural network provides a simple way of modeling, for non-linear characteristics of the machine [19]-[21].

In this paper, ANN modeling along with iterative technique has been proposed to analyze the steady-state performance of SEIG through conventional equivalent circuit. Iterative modeling estimates the unknown frequency and magnetizing reactance. ANN has been proposed to model the nonlinear magnetizing characteristics of the machine. Computed results have been compared with the results obtained using commonly adopted technique (piecewise linear approximation of magnetization curve) as well as with the experimental results.

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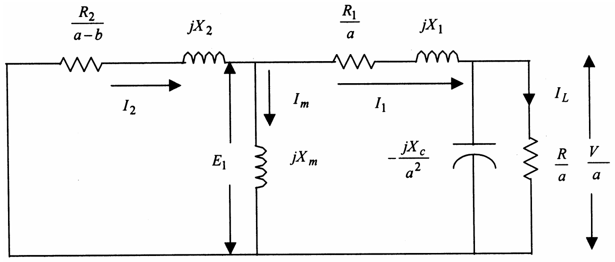

Fig. 1. Per phase equivalent circuit representation for self-excited induction generator.

The comparison gives the validity and accuracy of the proposed model using ANN.

II. MODELING OF SEIG

The steady-state operation of the self-excited generator may be analyzed by using the conventional equivalent circuit representation [8] as shown in Fig. 1.

In this circuit model all parameters are assumed to be independent of saturation except for magnetizing reactance. Here magnetizing reactance will be saturated one for generator operation, which is not so for motoring mode. Analysis of equivalent circuit of Fig. 1 results into the following equations for steady-state operation as generator

$$\frac{\left(R_L+\frac{R_1}{a}\right)}{\left(X_1-X_L\right)^2+\left(R_L+\frac{R_1}{a}\right)^2}+\frac{\frac{R_2}{a-b}}{X_2^2+\left(\frac{R_2}{a-b}\right)^2}=0 \qquad (1)$$

$$-\frac{1}{X_m}-\frac{X_2}{X_2^2+\left(\frac{R_2}{a-b}\right)^2}-\frac{\left(X_1-X_L\right)}{\left(X_1-X_L\right)^2+\left(R_L+\frac{R_1}{a}\right)^2}=0 \qquad (2)$$

where $R_L=\frac{RX_C^2}{(a(a^2R^2+X_C^2))}$ and $X_L=\frac{R^2X_C^2}{(a^2R^2+X_C^2)}$.

III. ITERATION TECHNIQUE

With low operating slips (1) can be modified as

$$s=-\frac{R_2(aR_L+R_1)}{a^2(X_1-X_L)^2+(aR_L+R_1)^2} \qquad (3)$$

where generated frequency is

$$a=\frac{b}{1-s}. \qquad (4)$$

Use of a too approximate equivalent circuit representation omitting stator impedance and rotor reactance results into the operating slip as

$$s=-\frac{R_2}{R} \qquad (5)$$

Equations (4) and (5) may be used to compute the initial value of frequency a_0 (to start the iteration process) as

$$a_0=\frac{b}{1+\frac{R_2}{R}} \qquad (6)$$

Once the initial value for generated frequency is known, the iteration process may be carried out using the following steps:

1. Computations of initial value of frequency a_0 from (6).
2. Estimation of the value of s from (3) after substituting the value of a as a_0.
3. Finding of the new value of generated frequency a' using the computed value of slip obtained in step 2, from (4).
4. Comparison of the new value of frequency a' with previous frequency used in step 2 i.e. a_0.

   If $|a'-a_0| \langle \varepsilon$ where $\varepsilon = 0.00000001$
   Then a' may be treated as generated frequency, otherwise process may be repeated by replacing a_0 with a' until difference in the successive values for generated frequency comes out to be ε.

The computed results on machine-1 (Appendix) using iteration technique have been shown in Table I.

Now this value of generated frequency has been used to compute the magnetizing reactance, X_m, using (2) as

$$X_m=-\frac{1}{\frac{X_2}{X_2^2+(\frac{R_2}{a-b})^2}+\frac{(X_1-X_L)^2}{(X_1-X_L)^2+(R_L+\frac{R_1}{a})^2}} \qquad (7)$$

Computed value of X_m from (7) is used to estimate the air gap voltage, which will make the complete resolution of the equivalent circuit of SEIG.

IV. MAGNETIZATION CHARACTERISTICS

Magnetization characteristics of induction machine are important for the analysis of SEIG. The nonlinear magnetization curve of the SEIG is the only source to develop the relationship between magnetizing reactance and air gap voltage. This air gap voltage influences the terminal conditions. Therefore, it becomes essential to develop a model for representation of magnetization curve.

In this paper, an ANN based modeling has been adopted for the representation of magnetization characteristics for machine-1. It has been compared with piecewise linear approximation modeling (already used by other researchers).

1) Piecewise Linear Approximation Modeling (PLA)

The nonlinear relationship between magnetizing reactance X_m and air-gap voltage E_1 using experimental data for machine-1 may be represented by PLA as below

$$\begin{array}{rl} X_m < 169.20 & E_1 = 512.69 - 2.13X_m \\ 179.42 > X_m \geq 169.20 & E_1 = 891.66 - 4.37X_m \\ 184.46 \geq X_m \geq 179.42 & E_1 = 785.79 - 3.78X_m \\ X_m > 184.46 & E_1 = 0 \end{array}$$

2) ANN Based Modeling

In this paper, the multilayer back propagation feed forward neural network has been used to develop a model that provides a good estimate of magnetization characteristics. The structure of ANN used in this paper has been shown in Fig. 2.

In this network, X_m is used as input and E_1 as output for training purpose. The network is set with 'logsig'

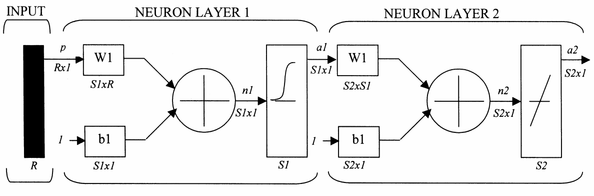

Fig. 2. Structure of the artificial neural network.

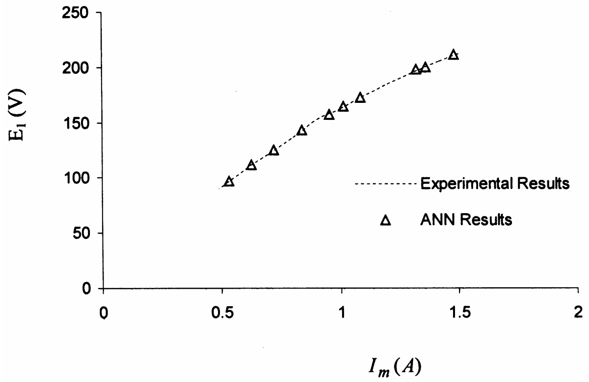

Fig. 3. Magnetization characteristics of SEIG.

TABLE I
RESULTS DETERMINATION OF GENERATED FREQUENCY $(C = 23.75\mu F)$

Number of iterations	Generated frequency, a				
	R =750 Ω	*R* =280 Ω	R =253 Ω	*R* =241 Ω	*R* =209.5 Ω
Initial value	0.96571355	1.01097069	1.02282887	1.02706895	1.04393674
1.	0.96044145	1.00384177	1.01533065	1.01943272	1.03579424
2.	0.96050650	1.00396630	1.01546947	1.01957761	1.03596190
3.	0.96050570	1.00396414	1.01546691	1.01957488	1.03595846
4.	0.96050571	1.00396418	1.01546696	1.01957493	1.03595853
5.	0.96050571	1.00396418	1.01546695	1.01957493	1.03595853
6.	0.96050571	1.00396418	1.01546695	1.01957493	1.03595853

activation function at the middle layer and 'purelin' activation function at the output layer. The design of the network and selection of optimum training parameters are performed by trial and error. Furthermore, Levenberg Marquardt training function is used which causes fewer epochs as compared to other training functions. Therefore, when an input is applied in the network, it will begin training based on the given data in order to produce the approximate results. This type of training has been found to be very effective for capturing the actual non-linear magnetization characteristics of induction machine.

V. RESULTS AND DISCUSSIONS

Fig. 2 shows the comparison of trained ANN results with experimental values for machine-1. The closeness of two indicates the accuracy of ANN modeling.

Table II presents the comparison of PLA technique, ANN technique and experimental values. Closeness between ANN and experimental results shows superiority of ANN modeling over PLA technique. Application of iterative technique along with ANN modeling and linear piecewise approximation for machine-1, results in the performance evaluating parameters such as generated frequency, terminal voltage, output power, stator current and capacitor current.

The results have been shown in Table III (a) and (b) along with experimental results. The comparison of computed results with experimental one gives the validity and accuracy of proposed modeling for SEIG using ANN technique.

Error levels and epochs required for different values of load resistance are shown in Table IV. Magnitude of error levels and number of epochs as shown gives the effectiveness of ANN modeling.

Application of the proposed technique to SEIG results in the performance characteristics as shown in Figs. 3-6. The nature of variation of terminal voltage, output power, stator current with load comes out be same as obtained by other researchers using the piecewise linear approximation. However, some differences appear at the light load conditions, which are due to mathematical modeling of the magnetic characteristics of induction generator.

As it is easy to capture the nonlinear characteristics using ANN as compared to the piecewise linear approximation, the results obtained by ANN technique seems to be accurate.

The terminal voltage falls sharply with load. This results in the poor voltage regulation for SEIG. However, it has been observed that this voltage can be controlled by proper control of excitation capacitance. The voltage increases with an increase in excitation capacitance for the given value of load and operating speed. Therefore, the excitation capacitance may be used as one of the control variables. Output power as shown in Fig. 4 increases with load as well as with excitation capacitance. For a given value of excitation capacitance, there is a load which results in the maximum output for SEIG. The turning point in Figs. 3-6 indicate the stable operating region for the machine. It is observed that the operating region for SEIG increases with an increase in excitation capacitance. The maximum loading capability for machine may be increased by the proper selection of excitation capacitance. However it comes to be about 47% in case of machine-1. It is due to the low value of unsaturated magnetizing reactance of test machine.

VI. CONCLUSIONS

In this paper an attempt has been made to realize the magnetic characteristics of induction machine for the computation of steady-state performance of SEIG using iterative technique. Computation of generated frequency using this iterative technique has been found to be very

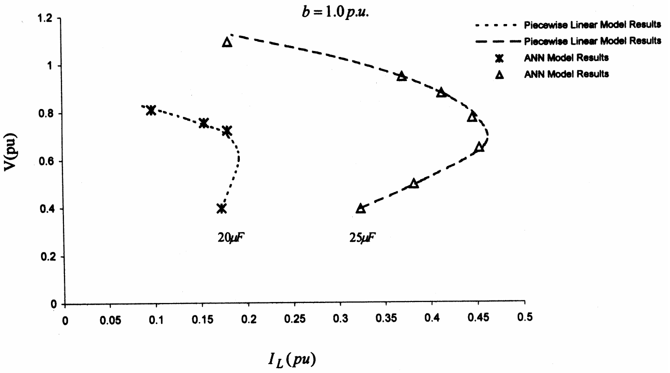

Fig. 4. Variation of terminal voltage with load.

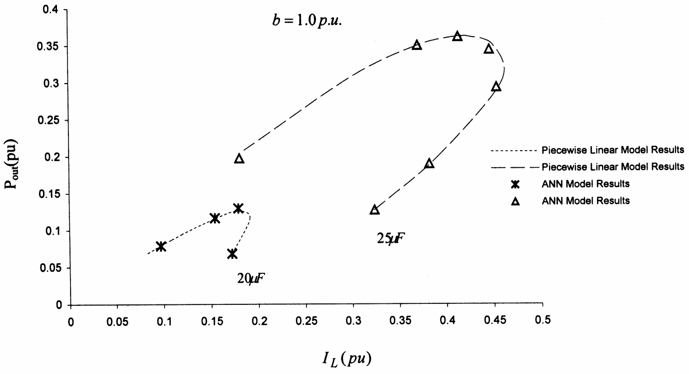

Fig. 5. Variation of output power with load.

TABLE II
COMPARISON OF PIECEWISE LINEAR APPROXIMATION AND ANN MODELING OF MAGNETIZATION CURVE

Sr. No	X_m (Ω)	Piecewise Linear Approximation Results E_1(V)	ANN Modeling Results E_1(V)	Experimental Results E_1(V)
1	184.46	88.530	88.530	88.540
2	179.42	107.58	107.59	107.60
3	173.90	131.71	121.69	121.70
4	170.50	146.57	136.40	136.40
5	169.20	152.25	152.28	152.30
6	162.20	167.20	162.21	162.20
7	53.90	184.88	184.70	184.70
8	144.50	204.90	205.19	205.20
9	141.30	211.72	211.90	211.90

TABLE III (A)
COMPARISON OF COMPUTED AND EXPERIMENTAL RESULTS (C=23.75 μF)

Sr. No.	R	b	By Iteration Model	Piecewise Linear Approximation Results		ANN Modeling Results		Experimental Results		
			a	V(pu)	P_{out} (pu)	V(pu)	P_{out} (pu)	a	V(pu)	P_{out} (pu)
1	750.0	0.976	0.960	0.963	0.142	0.967	0.143	0.960	1.0	0.153
2	300.0	1.033	0.999	1.001	0.386	0.998	0.383	0.999	1.0	0.384
3	290.0	1.036	1.001	1.004	0.401	1.000	0.398	1.002	1.0	0.398
4	280.0	1.0 0	1.003	1.004	0.415	1.001	0.413	1.004	1.0	0.412
5	270.0	1.044	1.006	1.005	0.432	0.995	0.424	1.008	1.0	0.427
6	253.0	1.055	1.015	1.022	0.477	1.013	0.468	1.016	1.0	0.456
7	241.0	1.061	1.019	1.024	0.502	1.013	0.492	1.019	1.0	0.479
8	231.0	1.067	1.024	1.029	0.529	1.011	0.511	1.024	1.0	0.499
9	221.0	1.074	1.029	1.033	0.557	1.029	0.553	1.029	1.0	0.522
10	209.5	1.084	1.035	1.039	0.596	1.032	0.588	1.036	1.0	0.551
11	199.0	1.091	1.041	1.039	0.626	1.030	0.615	1.041	1.0	0.580

TABLE III (B)
COMPARISON OF COMPUTED AND EXPERIMENTAL RESULTS (C=23.75 μF)

Sr. No.	R (Ω)	b	Piecewise Linear Approximation Results		ANN Modeling Results		Experimental Results	
			I_1 (pu)	I_C (pu)	I_1 (pu)	I_C (pu)	I_1 (pu)	I_C (pu)
1.	750.0	0.976	0.810	0.797	0.813	0.800	0.847	0.827
2.	300.0	1.033	0.944	0.862	0.941	0.859	0.957	0.860
3.	290.0	1.036	0.954	0.866	0.950	0.863	0.965	0.863
4.	280.0	1.040	0.962	0.868	0.959	0.866	0.973	0.865
5.	270.0	1.044	0.972	0.872	0.962	0.863	0.978	0.868
6.	253.0	1.055	1.009	0.894	1.000	0.886	1.005	0.875
7.	241.0	1.061	1.025	0.899	1.014	0.890	1.021	0.878
8.	231.0	1.067	1.043	0.907	1.025	0.892	1.031	0.882
9.	221.0	1.074	1.063	0.916	1.059	0.912	1.052	0.886
10.	209.5	1.084	1.090	0.928	1.083	0.921	1.073	0.892
11.	199.0	1.091	1.110	0.932	1.100	0.924	1.084	0.897

simple. ANN modeling has been found to be very effective for accounting the non-linearity of magnetic characteristics. Further, it is observed that ANN completely captures the nonlinear magnetizing characteristics of SEIG. Comparison of the computed results using ANN modeling along with iteration technique have been compared with the experimental results. A close agreement between the computed and experimental results confirms the validity

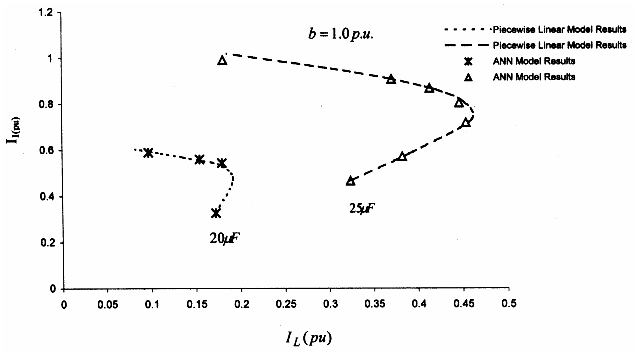

Fig. 6. Variation of stator current with load.

and accuracy of the analysis of SEIG using ANN modeling. Such a simple, unique and accurate modeling will be useful to evaluate the behaviour of SEIG, which is found to be most suitable choice for wind energy conversion in remote windy areas.

APPENDIX

The details of machine-1;

- Specifications
  3-phase, 4-pole, 50 Hz, star connected, squirrel cage induction machine
  0.750 kW/1HP, 380V (rated line voltage), 1.90 A.
- Specifications
  $R_1 = 9.5\Omega, R_2 = 8.04\Omega, X_1 = X_2 = 8.84\Omega$
- Base values
  Base voltage =219.30 V
  Base current =1.90 A
  Base impedance=115.40 Ω
  Base Capacitance=27.5 μF
  Base power=1.25 kW
  Base frequency=50 Hz
  Base speed=1500 rpm

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TABLE IV
ERROR LEVELS AND EPOCHS

Sr. No.	Error Level	Epochs Required
1	4.50244e-008	07
2	2.48387e-008	27
3	2.48387e-008	27
4	4.50244e-008	07
5	1.70792e-008	69
6	4.50243e-008	07
7	5.53281e-008	78
8	1.70792e-008	69
9	1.78433e-009	06
10	2.71858e-008	23
11	1.22133e-009	05

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