Steady State Modeling of Isolated Induction Generators

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Abstract – Isolated induction generators usually called self-excited induction generators seem to be most suitable machines for wind energy conversion in remote and windy areas. Estimation of steady state performances for such machines is must to encounter the problems, which may appear under real operating conditions. In this paper, a new and simple modeling approach, including a unique equivalent developed by the author, is adopted to analyze the steady state performance of a self-excited induction generator (SEIG). The study reveals that the performance of self-excited induction generator is greatly influenced by the operating speed and excitation capacitance. This gives an opportunity for proper handling of these parameters to obtain the required performance characteristics. Constant frequency and iterative models have been proposed for the analysis and control of SEIG. Simulated results as obtained have been compared with experimental results on a test machine and found to be in close agreement.

Key-words –Isolated Induction Generator, Renewable Generation, Steady State Analysis (SSA), Self- Excited Induction Generator, Wind Energy Generation,

NOMENCLATURE

a	per unit frequency
b	per unit speed
C	excitation capacitance per phase
E_1	air gap voltage per phase at rated frequency
E_2	rotor emf per phase referred to stator
E_a	air gap voltage per phase= aE_1
f	rated frequency
I_1	stator current per phase
I_2	rotor current per phase, referred to stator
I_L	load current per phase
I_m	magnetizing current per phase
P_{out}	output power
R	load resistance per phase
R_1	stator resistance per phase
R_2	rotor resistance per phase, referred to stator
	generator slip
V	terminal voltage per phase
X_1	stator reactance per phase
X_2	rotor reactance per phase, referred to stator
X_c	capacitive reactance due to C at rated frequency
X_m	magnetizing reactance per phase at rated frequency

1. Introduction

It is found that self-excited induction generators (SEIG) are most suitable for many applications including wind and small hydroelectric energy conversion systems. Such generators may also be used for lighting or cooking purpose to minimize the requirement of conventional fuels in the remote areas. SEIG has many advantages such as brushless construction (squirrel-cage rotor), reduced size, absence of DC power supply for excitation as in conventional generators, reduced maintenance cost, self short-circuit protection capability and no synchronizing problem.

Proper circuit representation and accurate mathematical modeling is must to evaluate the steady-state performance of a SEIG for different operating conditions. In order to estimate the performance of a SEIG, researchers have made use of the conventional equivalent circuit of an induction motor. Some of the researchers [1-7] used the impedance model, and a few [8-11] used the admittance-based model for such computations. However it has been felt that the old conventional equivalent circuit model, in the absence of an active source, does not effectively correspond to generator operation. Therefore [10-12] suggested a new circuit model for the representation of induction generator. Further it is found that most of the researchers uses the modeling, which results in to a single polynomial equation of higher order in unknown generated frequency and magnetizing reactance.

This paper is an attempt to present two techniques (with new equivalent circuit model developed by the author) to analyze the steady state operation of a self-excited induction generator (SEIG). Proposed analysis needs only the solution of quadratic equation, irrespective of operating conditions. Computed results using proposed methodology have been compared with experimental results. The closeness between experimental and computed results confirms the validity of the proposed modeling.

2. Steady State Equivalent Circuit Model

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

Further, this network may be modified to a more practical format as given by Fig. 2, wherein $E_a(1+s)$ represent source voltage corresponding to mechanical power transformed to electrical power through rotor.

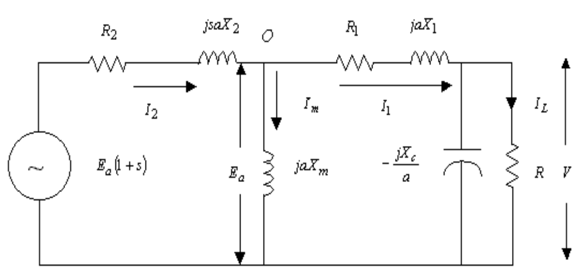

Fig. 1. Per phase equivalent circuit representation for self-excited induction generator.

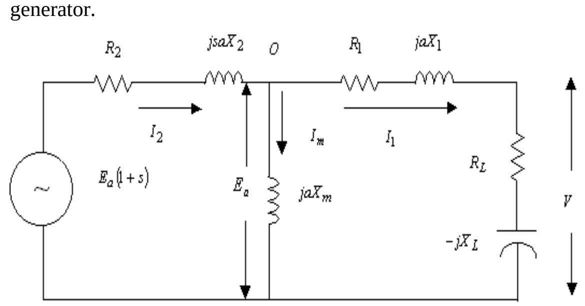

Fig. 2. Modified per phase equivalent circuit representation for self-excited induction generator.

Where,

$$R_L = \frac{R X_c^2}{a^2 R^2 + X_c^2}$$
$$X_L = \frac{a R^2 X_c}{a^2 R^2 + X_c^2} \qquad (1)$$

3. Constant Frequency Model

Circuit analysis of Fig. 2 results in to the following;

$$A_2 s^2 + A_1 s + A_0 = 0 \qquad (2)$$

Where,

$$A_2 = a^2 X_2^2 R_{1L}$$
$$A_1 = -R_2\left(R_{1L}^2 + X_{1L}^2\right)$$
$$A_0 = R_{1L} R_2^2$$
$$R_{1L} = R_1 + R_L$$
$$X_{1L} = aX_1 - X_L$$

&

$$b = a\,(1+s) \qquad (3)$$

It is observed that equation (2) in terms of slip always comes to be quadratic expression irrespective of nature of load. Equation (2) & (3) may be used to determine the operating speed to generate a particular frequency for given value of excitation capacitance and load resistance. This gives an opportunity to control the generated frequency. Further following expression as obtained from the analysis may be used to determine the saturated value of magnetizing reactance.

$$X_m = \left[\frac{-R_2\left(R_{1L}^2 + X_{1L}^2\right)}{sa^2 X_2 R_{1L} + aR_2 X_{1L}}\right] \qquad (4)$$

X_m as obtained may be used to determine the value of air gap voltage' E_1 ' using Appendix-2.

4. Iteration Model

Approximate equivalent circuit representation of induction generator, after omitting stator impedance and rotor reactance, results in the operating slip as;

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

Where generated frequency is

$$a = \frac{b}{1+s} \qquad (6)$$

Equation (5) and (6) may be used to compute the initial value of frequency a_0 (to start the iteration process) as;

$$a_0 = \frac{b}{1 + \frac{R_2}{R}} \quad (7)$$

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 (7).
2. Estimation of the value of s from (2) 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 (6).
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 ε =0.00000001

   Then a' may be treated as generated frequency, other wise process may be repeated by replacing a_0 with a' until difference in the successive values for generated frequency comes out to be ε.

   Proposed modeling may be used to estimate the generated frequency of SEIG. Further X_m may be obtained using (4), which gives the value of air gap voltage using magnetization curve. Once air gap voltage 'E_1' at rated frequency is known, then the performance of the machine may be obtained using equivalent circuit representations as given by Fig. 1 and Fig. 2.

5. Operating Limits

Equation (2) & (3) gives the expression for operating slip as

$$s = \frac{R_2(R_{1L}^2 + X_{1L}^2) \pm R_2\sqrt{(R_{1L}^2 + X_{1L}^2)^2 - 4a^2 R_{1L}^2 X_2^2}}{2a^2 X_2^2 R_{1L}} \quad (8)$$

The above equation gives two possible values of slip to which the stipulated operating conditions confirm too. But only the lower of the two values is relevant for generating mode.

This slip will be real only if

$$R_{1L}^2 + X_{1L}^2 \geq 2a\ R_{1L}\ X_2 \quad (9)$$

If the limiting value (minimum) of (R_{1L}^2 + X_{1L}^2) given by equation (9) is substituted in equation (8), it gives the maximum possible value of operating slip for a given combination of exciting capacitance and rotor speed as

$$s_{max} = \frac{R_2}{a\,X_2} \quad (10)$$

But it is to be noted that for the limiting value given by equation (10), the load on the machine becomes so large that the operation as generator fails.

Further equation (9) gives

$$\frac{R_{1L}}{R_{1L}^2 + X_{1L}^2} < \frac{1}{2aX_2} \quad (11)$$

Modification of equation (11) with the assumption that $(saX_2)^2 << (R_2)2$ which is true for low operating slips, gives;

$$s < \frac{R_2}{2aX_2} \quad (12)$$

The above equation gives the limiting value of slip for the generator operation. Thus limiting value of the operating slip in terms of s_{max} is;

$$s < \frac{s_{max}}{2} \quad (13)$$

This implies that generator operation is not possible up to S_{max}.

6. Identification of Control Parameters

In self-excited induction generator, terminal voltage and frequency varies with operating conditions. However these may be controlled by proper control of operating parameters such as excitation capacitance, speed etc.

6.1 Excitation Capacitance

It is well known that a SEIG always operates at a leading power factor. To meet this condition 'X_{1L}' as defined in section 3 must be negative.

To fulfil this condition,

$$R > \sqrt{\frac{X_1 X_c^2}{X_c - a^2 X_1}} \qquad (14)$$

In this, R will be real and positive only when
$X_c \geq a^2 X_1$
If $X_c = a^2 X_1$, then , $R \to \infty$,
Hence machine is not in a position to deliver the load under such conditions. Excitation shall meet only the VAr requirement of stator, where as in case of induction generator the capacitance must be sufficient to meet the total VAr requirements of the machine.
In case $X_c >> a^2 X_1$, then

$$R > (X_1 X_C)^{1/2}$$

This is the load capability of the machine up to which a self-excited induction generator may be loaded for a given value of excitation capacitance.
As X_c is inversely proportional to C, increase in the value of capacitor will reduce the value of X_c, thus decreasing the effective value of load resistance. This implies that the load capacity of the machine increases with an increase in the value of excitation capacitance.

6.2 Operating Speed

It has been observed that the operating speed of machine is almost linearly related to generated frequency for a given set of operating conditions. Thus any change in the speed affects the generated frequency and plays an important role to control it.
Further any change in generated frequency affects the effective value of excitation reactance. The effective value of excitation reactance decreases with any increase in the frequency, which in turn increases with an increase in the operating speed. Thus any increase in the speed will result in to a reduction in the excitation reactance. This in turn is equivalent to the effect due to an increase in the capacitance. Therefore an increase in the operating speed with constant excitation capacitance and load resistance will result in to an increase in the terminal voltage.

5. Results & Discussions

Constant frequency and iteration model as discussed above, were applied on test machine (Appendix-2). Table 1 and Table 2 give a comparison of computed and experimental results on test machine. These are found to be in good agreement, and so confirm the validity of the proposed modeling.

Table1. Experimental verification of constant frequency model

Speed(rpm)	Computed Values		Experimental Values	
	Frequency(Hz)	Voltage(V)	Frequency(Hz)	Voltage(V)
C=36μF,R=160 Ω				
1467	48.3	158.6	48.3	158
1498	49.3	178.3	49.35	176
1516	49.9	188.1	49.92	189
1543	50.76	201.9	50.74	203
C=36 μF, R=220 Ω				
1467	48.43	173.8	48.28	171
1496	49.4	190.3	49.24	188
1540	50.8	213.1	50.78	210

Table2. Experimental verification of iteration model

Speed(rpm)	Computed Values		Experimental Values	
	Frequency(Hz)	Voltage(V)	Frequency(Hz)	Voltage(V)
C=36 μF,R=160 Ω				
1467	48.29	158.4	48.3	158
1498	49.3	178.4	49.35	176
1516	49.89	188.1	49.92	189
1543	50.78	202.4	50.74	203
C=36 μF, R=220 Ω				
1467	48.44	174.5	48.28	171
1496	49.39	190.3	49.24	188
1540	50.84	213.8	50.78	210

Fig. 3 to Fig. 5 shows the variation of terminal voltage, magnetizing reactance and frequency with excitation capacitance as simulated results on test machine. Here the operating speed of the machine is kept constant as 1 pu. It is felt that any change in the excitation capacitance affects the terminal voltage, magnetizing reactance, generated frequency and load delivered by the machine. Thus the load carrying capacity of the machine may be controlled by change of excitation capacitance and it may act as a control parameter in case of self-excited induction generator.

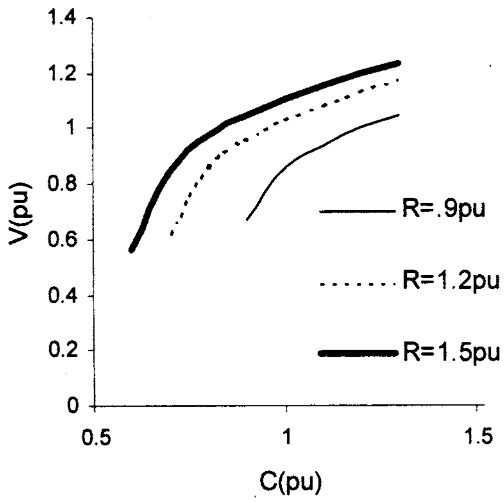

Fig. 3 Variation of voltage with excitation capacitance, b=1pu

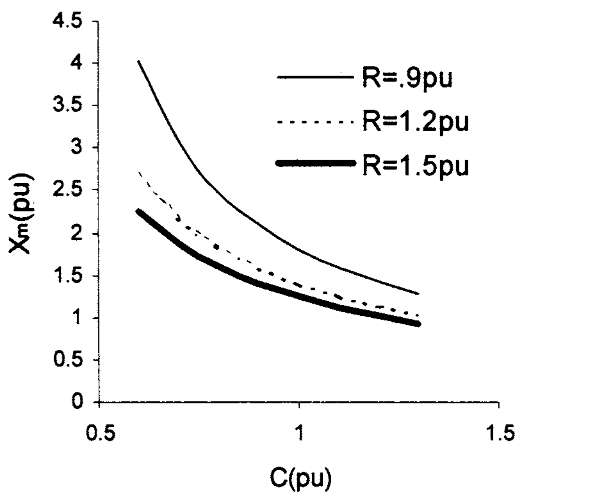

Fig. 4 Variation of magnetizing reactance with excitation capacitance, b=1pu

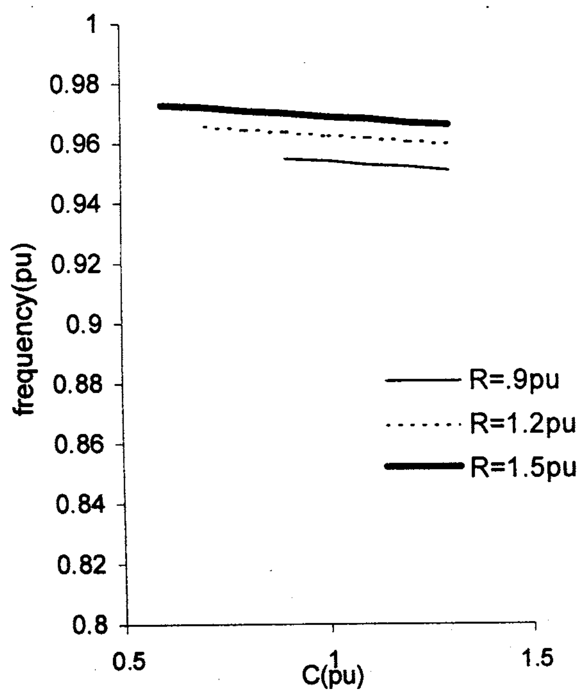

Fig. 5 Variation of frequency with excitation capacitance, b=1pu

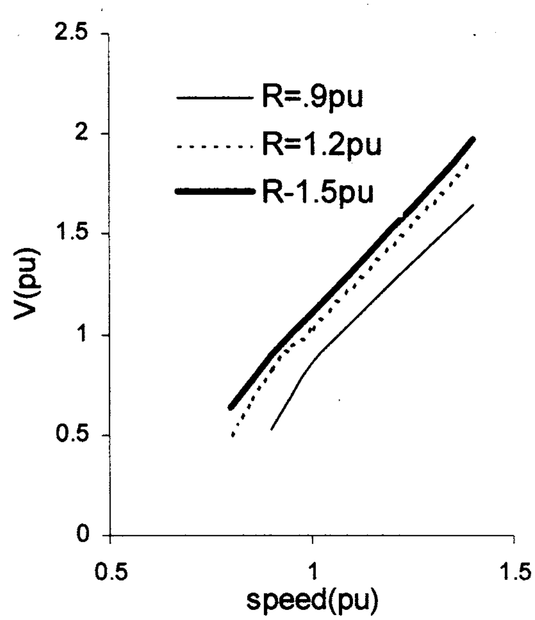

Fig. 6 Variation of voltage with operating speed, C=1pu

Fig. 6 to Fig. 7 gives the variation in the terminal voltage and generated frequency with the operating speed as simulated results on test machine, under given operating condition. It is found that any change in the operating speed effects terminal voltage as well as generated frequency Therefore similar to excitation capacitance operating speed becomes another control variable.

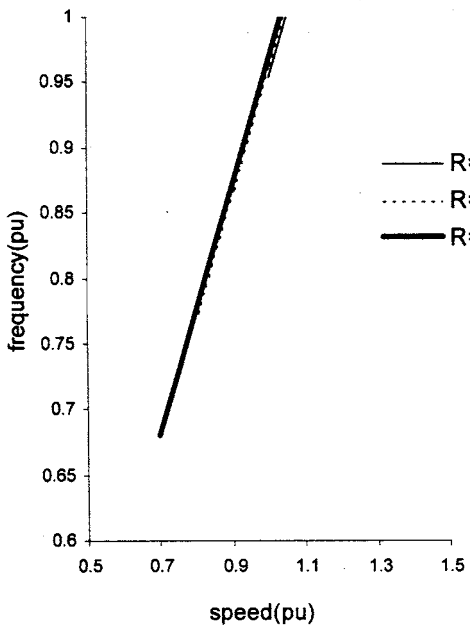

Fig. 7 Variation of frequency with operating speed, C=1pu

7. Conclusion

In this paper an attempt has been made to propose new and simple models for the steady state analysis of self-excited induction generator. Closeness between computed and experimental results proves the validity of proposed analysis. Proposed modelling results in the solution of a quadratic equation in contrast to higher order polynomial as obtained by other research person. It has been extended to estimate the operating zone of induction generator. Further controlled parameters have been identified which may be helpful in maintaining the terminal conditions of the generator. As observed from results, constant frequency and iteration model both may be adopted for complete analysis and control.

Appendix-1

The usual equivalent circuit representation for a three-phase induction motor is shown in Fig. 8 (a). This circuit may be redrawn as shown in Fig. 8 (b) and 8 (c). In Fig. 8(c) the sink voltage is given by $E_2(1-s)$; E_2 being equal to $I_2(R_2/s+jX_2)$. In case of generator operation, the sink voltage becomes source voltage with slip as negative. The corresponding equivalent circuit is shown in Fig. 8 (d).

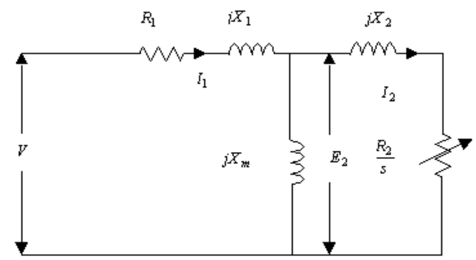

Fig. 8 (a)

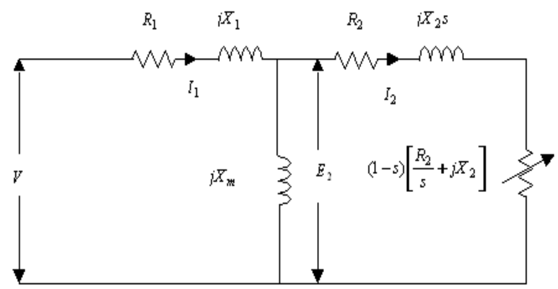

Fig. 8 (b)

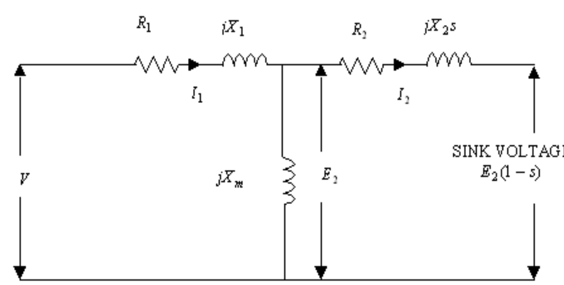

Fig. 8 (c)

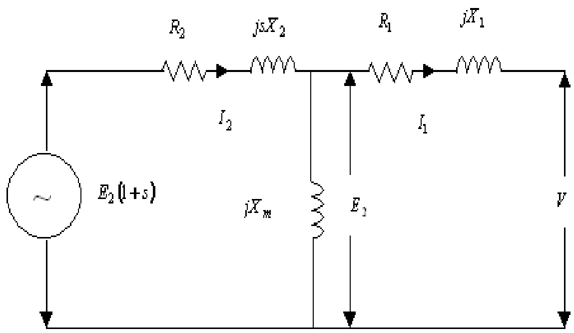

Fig. 8 (d)

Fig. 8 Equivalent circuit representation for induction generator

Appendix-2

The details of the Induction Machine used to obtain the experimental results are;

- Specifications

3-phase, 4-pole, 50 Hz, delta connected, squirrel cage induction machine
2.2kW/3HP, 230 V, 8.6 A

- Parameters

The equivalent circuit parameters for the machine in pu are
$R_1 = 0.0723, R_2 = 0.0379, X_1 = X_2 = 0.1047$.

- Base values

Base voltage =230 V
Base current =4.96 A
Base Impedance=46.32 Ω
Base frequency=50 Hz
Base speed=1500rpm
Base capacitance= 68.71μ F

- Air gap voltage

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

$$X_m < 82.292 \qquad E_1 = 344.411 - 1.61X_m$$
$$95.569 > X_m \geq 82.292 \qquad E_1 = 465.12 - 3.077X_m$$
$$108.00 > X_m \geq 95.569 \qquad E_1 = 579.897 - 4.278X_m$$
$$X_m \geq 108.00 \qquad E_1 = 0$$

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