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. In order to neutralize the effect of speed variations, modeling is extended to achieve rotor resistance control in case of wound rotor induction generator.

Key Words –Isolated Induction Generator, Renewable Generation, Steady State Analysis, 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
s	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

Due to preferred generation of alternating current power supply, synchronous generator has become the main attraction for its utility to extract the power from conventional sources of energy. Generally it is used in hydro and thermal power stations. These generators have undergone an impressive evolution in terms of their ratings, cooling methods and parameters. But the increasing rate of depletion of conventional sources of energy as well as growing power demand has diverted the attention of scientists towards the non-conventional sources of energy [1-6] such as

- Wind energy
- Solar energy
- Wave/Tidal energy
- Geothermal energy

Out of these wind energy is the fastest growing area of all renewable energy resources and is attractive and viable. It is observed that winds carry enormous amount of energy and could meet sufficient energy needs of the world. The regions in which strong winds prevail for a sufficient time during the year may use wind energy profitably for different purposes.

It has been found that cost of wind generation is comparable to that from hydro and thermal plants. There is a little doubt that while the cost of wind generation would be even lower in the coming few years, the prices of fossil fuels used by thermal plants would definitely go up. In view of high capital constructional cost hydel power would be dearer too. In addition to this wind energy generation provides a clean and pollution free environment. It does not lead to global warming and ozone depletion. No hazardous waste is created. Further a wind turbine generator may be a very worthwhile proposition for an isolated and remote area. To feed such an area from a power grid, long transmission lines are required. It needs huge investment. Diesel plants best serve such areas and a wind turbine generator may be installed to work in combination with diesel plant to meet the local demands. Such an operation will lead to saving in fuel and economy. On the whole these have given a great impetus to investment in research and technology. Bigger turbines, better blade design, advanced material, smart electronics and micro controls have all helped to improve the wind generation technology a lot.

There is a considerable interest 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 in addition to other advantages such as brush less construction (squirrel-cage rotor), reduced size in comparison to alternators, absence of DC power supply for excitation which is required in conventional generators, reduced maintenance cost, self short-circuit protection capability and no synchronizing problem. 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.

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 [7-13] used the impedance model, and a few [14-18] used the admittance-based model for such computations. [7-9] obtained the nonlinear equations in terms of unknown frequency and magnetizing reactance. Its solution requires application of Newton Raphson method. Whereas [10-11] analyzed the operation after decoupling the equations in unknown variables. Here analysis requires the solution of higher order polynomial in term of unknown frequency. [12] investigated the effects of excitation capacitance on the performance of SEIG. [13] suggested the design modifications of induction machine operating as generator. [14-15] used the nodal approach and obtained higher order polynomial equation in terms of unknown frequency. [16] tried to simplify the approach after including additional assumptions.

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 [17-18] 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.

Further efforts are made to propose a modeling to compensate the effect of speed variations on output of machine due to wind speed fluctuations. It may be achieved by controlling the rotor resistance in case of wound rotor induction generators.

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.

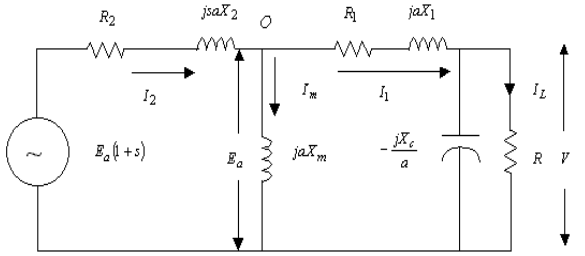

Fig. 1. Per phase equivalent circuit representation for self-excited induction generator.

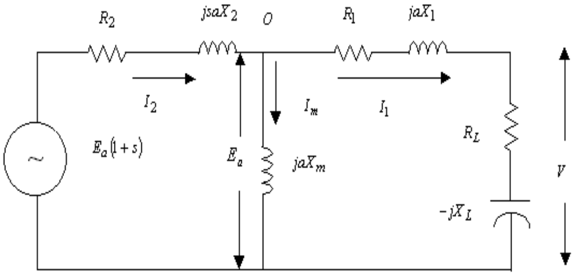

Fig. 2. Modified per phase equivalent circuit representation for self-excited induction generator.

Where,

$$\left.\begin{aligned} R_L &= \frac{RX_c^2}{a^2R^2+X_c^2} \\ X_L &= \frac{aR^2X_c}{a^2R^2+X_c^2} \end{aligned}\right| \qquad (1)$$

3. Constant Frequency Model

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

$$A_2s^2+A_1s+A_0=0 \qquad (2)$$

Where,

$$A_2 = a^2X_2^2R_{1L}$$

$$A_1=-R_2\left(R_{1L}^2+X_{1L}^2\right)$$

$$A_0 = R_{1L}R_2^2$$

$$R_{1L} = R_1 + R_L$$

$$X_{1L} = aX_1 - X_L$$

&

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

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 desired 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.

$$X_m=\left[\frac{-R_2\left(R_{1L}^2+X_{1L}^2\right)}{sa^2X_2R_{1L}+aR_2X_{1L}}\right] \qquad (4)$$

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;

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

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 $\left|a'-a_0\right|\langle\varepsilon$, 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

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

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

$$R_{1L}{}^2 + X_{1L}{}^2 \geq 2a\ R_{1L}\ X_2 \tag{9}$$

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;

$$s_{max}=\frac{R_2}{a\,X_2} \tag{10}$$

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

$$\frac{R_{1L}}{R_{1L}^2+X_{1L}^2}<\frac{1}{2aX_2} \tag{11}$$

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

$$s<\frac{R_2}{2aX_2} \tag{12}$$

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;

$$s<\frac{s_{max}}{2} \tag{13}$$

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

It is well known that under induction machine operation as a generator, the slip is negative. This negative slip results in to a negative internal torque developed, which is called generating torque. The generating torque T_G developed by the machine in synchronous-watts is given as

$$T_G=3I_2^2\frac{R_2}{s} \tag{14}$$

Where,

$$I_2 = \frac{saE_1}{\sqrt{R_2^2 + s^2 a^2 X_2^2}} \qquad (15)$$

This gives;

$$T_G = 3\frac{s^2 a^2 E_1^2}{R^2 + s^2 a^2 X_2^2}\left(\frac{R_2}{s}\right) \qquad (16)$$

In case $S^2a^2X_2^2$ is negligible as compared to R_2^2 (which is justified for low operating slips), the above expression becomes;

$$T_G = \frac{3sa^2E_1^2}{R_2} \qquad (17)$$

From above it is clear that in case of induction generator the air-gap torque also depends upon generated frequency in addition to the voltage and is controllable through rotor resistance in case of slip ring induction generators.

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. Rotor resistance appears to be another control parameter in case of wound rotor induction generators

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 fulfill this condition,

$$R > \sqrt{\frac{X_1 X_c^2}{X_c - a^2 X_1}} \qquad (18)$$

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 loading. 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.

6.3 Rotor resistance control

Analysis of real components of the currents at node 'O' in Fig.2 by replacing R_2 with R_{2e} gives-

$$\frac{s R_{2e}}{R_{2e}^2 + s^2 a^2 X_2^2} - \frac{R_{1L}}{R_{1L}^2 + X_{1L}^2} = 0 \qquad (19)$$

After rearrangement it leads to,

$$Q_2 R_{2e}^2 + Q_1 R_{2e} + Q_0 = 0 \qquad (20)$$

Where,

$$Q_2 = -R_{1L}$$

$$Q_1 = s\left(R_{1L}^2 + X_{1L}^2\right)$$

$$Q_0 = -a^2 s^2 R_{1L} X_2^2$$

$R_{2e} = R_2 + R_{ext}$

R_{2e}=Effective rotor resistance per phase in case of wound rotor induction machine.

R_{ext}=External resistance per phase connected in series of rotor circuit

Equation (20) may be used to determine the external rotor resistance required in case of wound rotor induction generators to compensate speed variations if any.

7. Results & Discussions

Constant frequency and iteration model as discussed above, were applied on machine-1 (Appendix-2). Table 1 and Table 2 give a comparison of computed and experimental results for machine-1. 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=36 micro farads, R=160 Ω				
1433	47.16	133.5	47.19	134
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
1570	51.66	216.4	51.69	217
1596	52.5	230	52.54	228
C=51 micro farads, R=160 Ω				
1280	42.1	163.5	42.17	166
1321	43.46	185.3	43.5	187
1353	44.5	199.1	44.67	201
1390	45.7	211.9	45.91	215
1440	47.33	228.7	47.4	232
C=36 micro farads, R=220 Ω				
1403	46.33	129	47.04	123
1442	47.63	157.5	47.64	154
1467	48.43	173.8	48.28	171
1496	49.4	190.3	49.24	188
1540	50.8	213.1	50.78	210
1563	51.6	226	51.13	224
C=51 micro farads, R=220 Ω				
1285	42.4	175.7	42.43	174
1315	43.4	191.8	43.41	187
1350	44.53	203.6	44.5	202
1386	45.73	216.4	45.7	216
1406	46.36	223.3	46.41	223
1430	47.16	231.7	47.62	237

Table2. Experimental verification of iteration model

Speed (rpm)	Computed Values		Experimental Values	
	Frequency (Hz)	Voltage (V)	Frequency (Hz)	Voltage (V)
C=36 micro farads, R=160 Ω				
1433	47.17	134.1	47.19	134
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
1570	51.66	216.7	51.69	217
1596	52.51	230.3	52.54	228
C=51 micro farads, R=160 Ω				
1280	42.11	163.8	42.17	166
1321	43.45	185.4	43.5	187
1353	44.5	199.2	44.67	201
1390	45.71	212	45.91	215
1440	47.34	229.2	47.4	232
C=36 micro farads, R=220 Ω				
1403	46.33	129.7	47.04	123
1442	47.61	157.9	47.64	154
1467	48.44	174.5	48.28	171
1496	49.39	190.3	49.24	188
1540	50.84	213.8	50.78	210
1563	51.59	226	51.13	224
C=51 micro farads, R=220 Ω				
1285	42.41	175.9	42.43	174
1315	43.39	191.8	43.41	187
1350	44.54	204.1	44.5	202
1386	45.72	216.7	45.7	216
1406	46.38	223.6	46.41	223
1430	47.17	232	47.62	237

Fig. 3 shows the simulated results on machine-1 using constant frequency model. This indicates the need to control speed of machine in a specific manner to generate constant frequency supply to accommodate the load variations. Fig. 4 to Fig. 6 gives the variation of terminal voltage, magnetizing reactance and frequency with excitation capacitance for machine-1. 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.

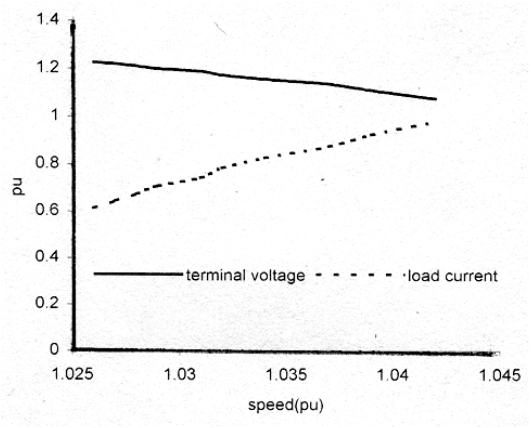

Fig. 3 Constant frequency operation, a=1pu, C=1pu

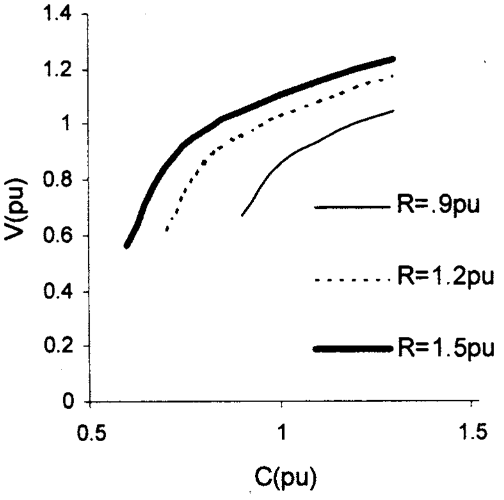

Fig. 4 Variation of voltage with excitation capacitance, b=1pu

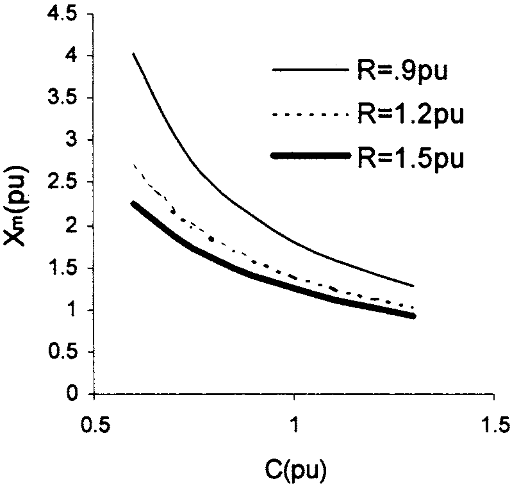

Fig. 5 Variation of magnetizing reactance with excitation capacitance, b=1pu

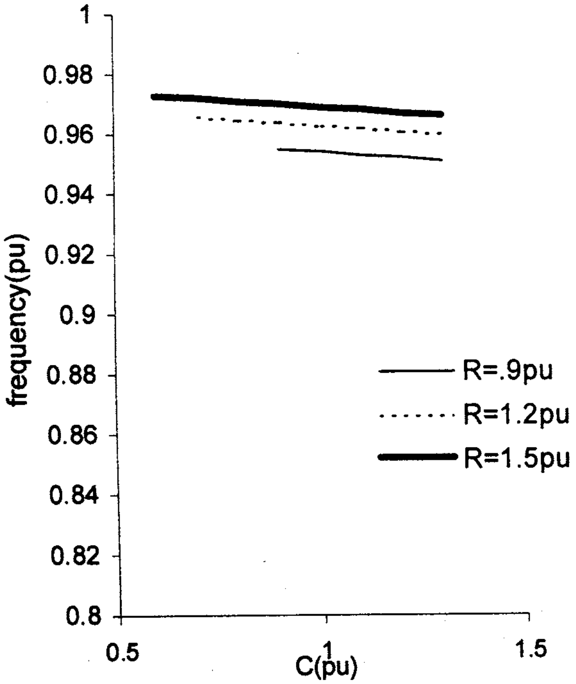

Fig. 6 Variation of frequency with excitation capacitance, b=1pu

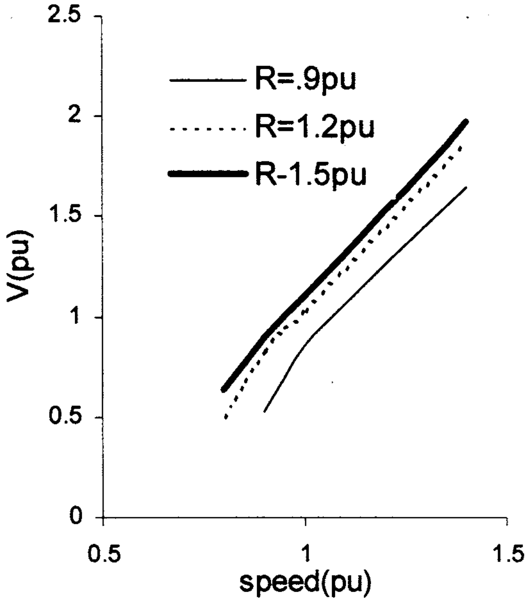

Fig. 7 Variation of voltage with operating speed, C=1pu

Fig. 7 to Fig. 8 gives the variation in the terminal voltage and generated frequency with the operating speed for machine-1 for a given value of excitation capacitance. 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.

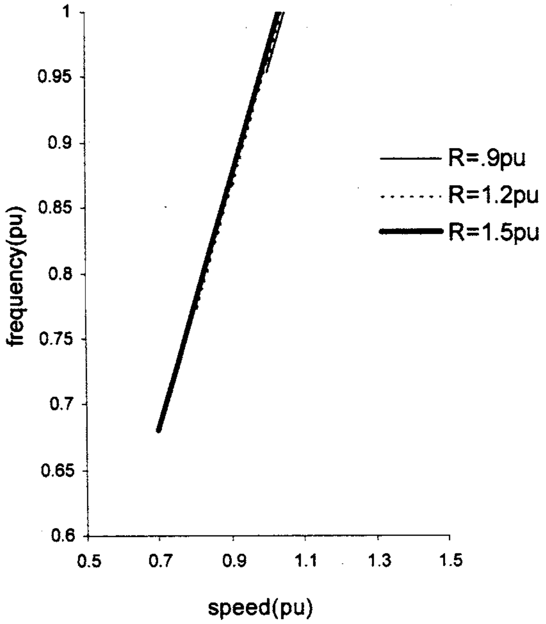

Fig. 8 Variation of frequency with operating speed, C=1pu

Table 3 gives the variation of external resistance required in case of wound rotor machine (Appendix-3) to maintain the terminal voltage and frequency. Any increase in the speed can be compensated by addition of appropriate value of external resistance. This gives the opportunity to maintain the output in case of wound rotor machines by proper control of rotor resistance.

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. Rotor resistance control is found to be effective to compensate speed variations due to wind speed fluctuations.

For future it is proposed to take up the work related to induction generators (generally employed in wind energy conversion) in the following areas.

- Application of artificial intelligence to control the operation of self-excited induction generator.
- Parallel operation of number of self-excited machines.
- Power quality problems associated with induction generators and control methodologies to improve the performance.

Present paper may be helpful to proceed with the research directions as mentioned above.

Table3. Estimation of external rotor resistance to maintain terminal voltage and frequency, C=1pu, R=1pu

Speed (pu)	R_{ext} (pu)	Terminal frequency (pu)	Terminal Voltage (pu)
1.114	0.001	1.0	1.07
1.123	0.007	1.0	1.07
1.131	0.013	1.0	1.07
1.14	0.020	1.0	1.07
1.149	0.026	1.0	1.07
1.158	0.032	1.0	1.07
1.167	0.039	1.0	1.07
1.175	0.045	1.0	1.07
1.184	0.052	1.0	1.07
1.193	0.058	1.0	1.07
1.202	0.062	1.0	1.07
1.21	0.071	1.0	1.07
1.219	0.077	1.0	1.07
1.228	0.083	1.0	1.07
1.237	0.090	1.0	1.07

Appendix-1

The usual equivalent circuit representation for a three-phase induction motor is shown in Fig. 9 (a). This circuit may be redrawn as shown in Fig. 9 (b) and 9 (c). In Fig. 9(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. Corresponding equivalent circuit is shown in Fig. 9 (d).

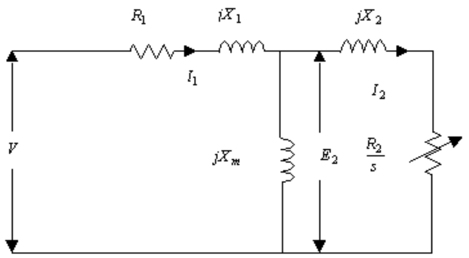

Fig. 9 (a)

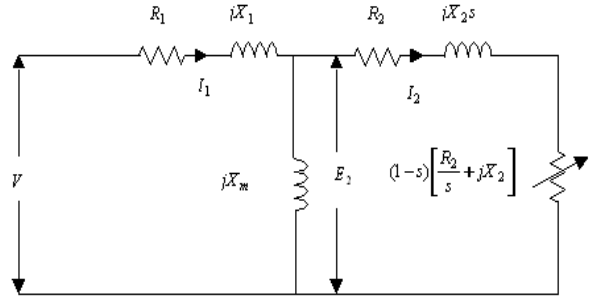

Fig.9 (b)

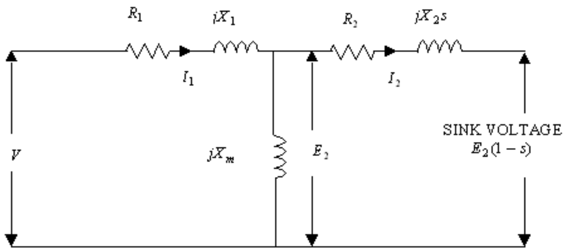

Fig. 9 (c)

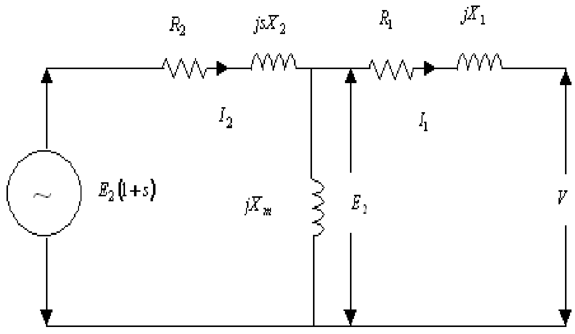

Fig. 9 (d)

Appendix-2

The details of the Machine-1 used to obtain the experimental and simulated 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.

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

Appendix-3

The details of the Machine-2 used to obtain simulated results are;

- Specifications

3-phase, 4-pole, 50 Hz, wound rotor induction machine
7 kW,
Stator - 400/231 V, 14.7/25.4 A
Rotor (Y) - 220 V, 19.5 A

- Parameters

R_1=1.05 ohm, R_2=1.296 ohm, X_1=X_2=2.61 ohms

- Base values

Base voltage=231 volt
Base current=14.7 A
Base impedance=15.71 ohm
Base capacitance=202.6 µF
Base frequency=50 Hz
Base speed=1500 rpm

- Air gap voltage

Piecewise segmentation of magnetization characteristics of machine results in to,

$$X_m < 51.2 \qquad E_1=277.53 - 1.42\ X_m$$
$$83.8 > X_m \geq 51.2 \qquad E_1=328.7 - 2.42\ X_m$$
$$95.2 > X_m \geq 83.8 \qquad E_1=349.44 - 2.67\ X_m$$
$$161.2 > Xm \geq 95.2 \qquad E_1=116.144 - 0.22\ X_m$$
$$X_m \geq 161.2 \qquad E_1=0$$

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