

PERFORMANCE EVALUATION OF A NINE-PHASE SELF- EXCITED INDUCTION GENERATOR

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Abstract. This paper evaluates the performance of a self-excited nine-phase induction generator. The advantage of using Multi-phases(more than three-phases)are well known such as High power handling capability by dividing the required power between multiple phases, higher reliability, reduced harmonics and Fault tolerant. For a nine-phase machine, if failure occurs the machine can still operate since each three phase group can be made independent from each other. In this study, mathematical model is developed directly from the equivalent circuit of nine-phase self-excited induction generator by means of nodal admittance method. The stator of a conventional 1.5 kW, 4-pole, 50 Hz three-phase squirrel cage induction machine has been modified to nine-phase induction machine. The excitation is provided by 9 capacitors each rated 40 μF and 450 V.

Key Words. Nine-phase, Self-excited induction generator, Performance Evaluation, Renewable Energy.

1. INTRODUCTION

Apart from their general use as motors, three-phase induction machines (IMs) are also used as generators in electric power systems. The induction generator offers advantages for hydro and wind applications in terms of cost and simplicity and it plays an important part in the renewable energy industry today [1, 2, 3]. However, the advantages of using Multi-phases system are well known such as High power handling capability by dividing the required power between multiple phases, reduced torque pulsations, higher reliability, reduced harmonics and fault tolerant. The induction generator has its limitations; it generally needs an external power source to provide its excitation. This means that it is difficult to employ in remote areas where there is no electrical power supply network. The possibility of using a Self-excited Induction Generator (SEIG) where a three-phase capacitor bank is connected across the stator terminals to supply the reactive power requirement of a load and generator was discovered by Basset and Potter in the 1930s [5]. When such an induction machine is driven by an external mechanical power source, the residual magnetism in the rotor produces an Electromotive Force (EMF) in the stator windings. This EMF is applied to the capacitor bank causing current flow in the stator winding and establishing a magnetizing flux in the machine [4, 5]. An induction machine connected and excited in this manner is capable of acting as a standalone generator supplying real and reactive power to a load. In this mode of operation, the capacitor bank supplies the reactive power requirement of the load and generator and the real power demand of the terminal load is supplied by the prime mover. The use of an induction machine as a generator is becoming more and more popular for renewable energy applications [3, 8, 9, 10, 11]. Squirrel cage induction generators with excitation capacitors (known as SEIGs) are popular in isolated non-conventional energy systems [2, 3, 6, 7]. However, the main drawback of the SEIG system is that the voltage and frequency produced by the system is highly dynamic under variable load conditions. Although many studies have been focused on regulating the voltage And frequency of

the SEIG system under variable loads, the regulation of speed and voltage does not result in a satisfactory level of performance due to the nonlinear behavior of the machine [12]. In this paper some aspects of performance of a nine-phase system are analyzed. The mathematical model using Nodal analysis for nine-phase self-excited induction generator (NPSEIG) is illustrated in details. Furthermore Practical measurements were carrying out to evaluate the process of voltage build up in NPSEIG. It should be noted that only no-load results are presented in this paper. Table 1 gives the machine specification and data, while Fig.1 and Fig. 2 show detailed winding arrangement of the NPSEIG and picture of a readily wound 9-phase stator, respectively.

Table 1: Machine Specification and Data

Description	Values
Number of phases	9
Stator external diameter	136 mm
Stator bore diameter	79 mm
Active axial length	112 mm
Number of poles	4
Number of stator slots	36
Number of turns per phase	132
Air-gap length	0.45
Rated kVA	2.205 kVA
Rated phase voltage	127 V
Average flux density	0.65 Wb/m ²
Frequency	50 Hz
Rated current	6.8 A
No-load current	2.78 A

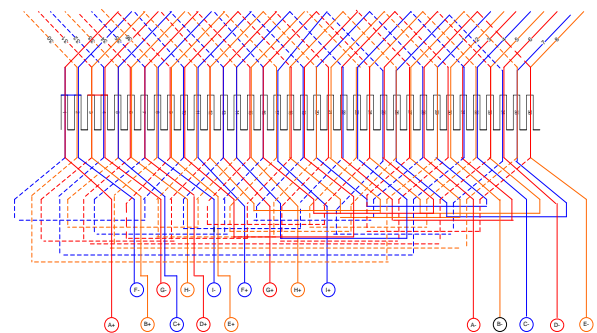


Fig. 1: Complete 9-phases winding housed in 36 slots



Fig. 2: Readily wound 9- phase stator (right) and squirrel cage (left)

2. PROPOSED MODEL

2.1. Mathematical model

Mathematical model of a NPSEIG using nodal analysis based on inspection is developed from the equivalent circuit of the generator. The developed model results in a matrix form that proves convenient for computer Simulation. The model must describe the characteristics of the individual components of the NPSEIG as well as the relations that govern the interconnections of these elements. The steady state equivalent circuit of nine-phase self-excited induction generator [4] is shown in Fig. 3.

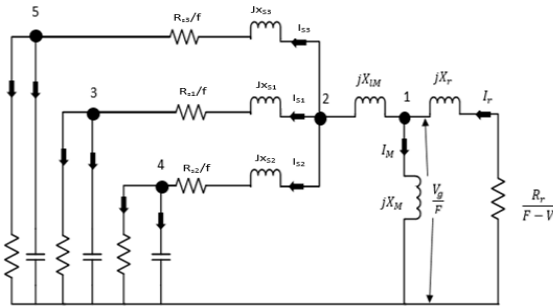


Fig. 3. Per phase equivalent circuit representation of nine-phase self-excited induction generator.

The above equivalent circuit is valid for any per unit speed v . The various elements of equivalent circuit are given from equations (1) to (12).

$$Y_1 = \frac{1}{\left[\frac{R_r}{(F-V) + jX_r} \right]} \quad (1)$$

$$Y_2 = \frac{1}{jXM} \quad (2)$$

$$Y_3 = \frac{1}{jXLm} \quad (3)$$

$$Y_4 = \frac{1}{\left[\frac{R_{s2}}{F + jX_{s2}} \right]} \quad (4)$$

$$Y_5 = \frac{1}{\left[\frac{R_{s1}}{F + jX_{s1}} \right]} \quad (5)$$

$$Y_6 = \frac{1}{\left[\frac{R_{s3}}{F + jX_{s3}} \right]} \quad (6)$$

$$Y_7 = \frac{1}{\left[\frac{-jX_{sh2}}{F} \right]} \quad (7)$$

$$Y_8 = \frac{1}{\left[\frac{RL_2}{F} \right]} \quad (8)$$

$$Y_9 = \frac{1}{\left[\frac{-jX_{sh1}}{F_2} \right]} \quad (9)$$

$$Y_{10} = \frac{1}{\left[\frac{RL_1}{F} \right]} \quad (10)$$

$$Y_{11} = \frac{1}{\left[\frac{-jX_{sh3}}{F_2} \right]} \quad (11)$$

$$Y_{10} = \frac{1}{\left[\frac{RL_3}{F} \right]} \quad (12)$$

The matrix equation presented based on nodal admittance method for the equivalent circuit they can be expressed as following

$$[Y][V] = [I S] \quad (13)$$

$[V]$ is the node voltage matrix, and $[I S]$ is the source current matrix. Where $[Y]$ is the nodal admittance matrix. The $[Y]$ matrix can be formulated directly from the equivalent circuit in fig. 3 using nodal admittance method based on inspection and as given in (14).

$$[Y] = \begin{bmatrix} Y_1 + Y_2 + Y_3 & -Y_3 & 0 & 0 & 0 \\ -Y_3 & Y_3 + Y_4 + Y_5 + Y_6 & -Y_5 & -Y_4 & -Y_6 \\ 0 & -Y_5 & Y_5 + Y_9 + Y_{10} & 0 & 0 \\ 0 & -Y_4 & 0 & Y_4 + Y_7 + Y_8 & 0 \\ 0 & -Y_6 & 0 & 0 & Y_6 + Y_{11} + Y_{12} \end{bmatrix} \quad (14)$$

Since, the equivalent circuit does not contain any current sources, $[I S] = [0]$ and hence Equation (1) is reduced as

$$[Y][V] = 0 \quad (15)$$

For successful voltage build up, $[V] \neq 0$ and therefore from Equation (3), $[Y]$ should be a singular matrix i.e., $\det [Y] = 0$. It implies that both the real and the imaginary components of $\det [Y]$ should be independently zero. Therefore to obtain required parameter which results $\det [Y] = 0$, genetic Algorithm based approach is implemented.

3. EXPERIMENTAL RESULTS

3.1 Experimental setup

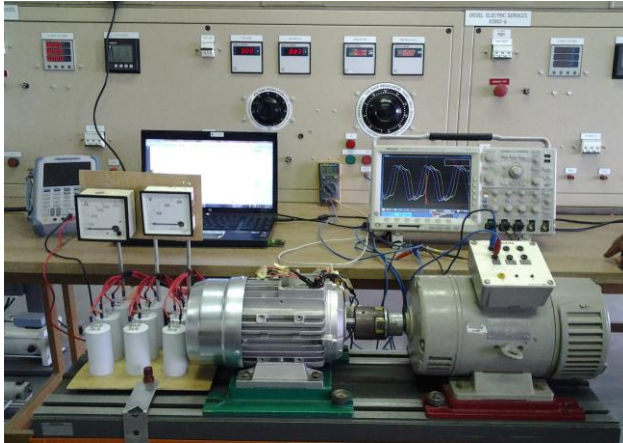


Fig. 4: Experimental setup rig photo

3.2 Analysis of Results

3.2.1 The Initial Self-excitation Process of the Induction Machine; No-load

The stator phase voltage starts building up slowly and reaches a steady-state value while the magnetization current starts from zero rising to a stable steady-state value. Table 2 gives the measured results on no-load with a capacitor of 40 μF per phase.

Table 2: Measured results on no-load

Speed (rpm)	V/phase (V)	I_o (A)	Q_c (VAR)	P (W)
1700	3.00	0.00	0.00	0.00
1800	4.20	0.05	0.63	0.00
1850	75.90	1.32	101	0.00
1900	98.60	1.84	195.1	4.80
2000	102.50	2.11	215.2	7.30
2050	119.50	2.55	295.4	10.10
2100	121.30	2.63	311.8	11.20
2150	127.20	2.28	366.1	17.80
2200	132.80	3.16	421.7	23.00

A stable output voltage could only be obtained once the machine's core is saturated. Another physical explanation of the starting process of the SEIG is that the residual magnetism presented in the core (the rotor) induces a small voltage across the stator windings and self-excitation capacitors once the rotor is driven by the prime mover. This produces a delayed current which in turn produces an increased voltage and consequently an increased capacitor current. This phenomenon goes on until saturation of the magnetic flux paths. Fig. 4 illustrates the stator Phase voltage builds up at no-load obtained from computer simulation.

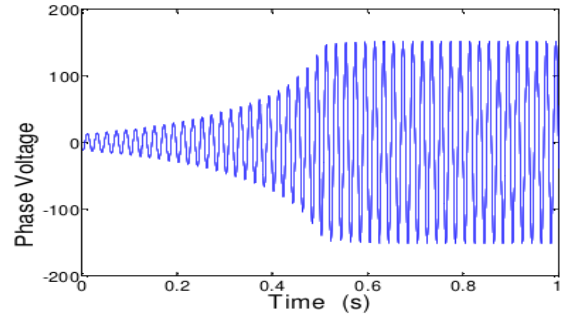


Fig. 5: Stator phase voltage builds up at no-load.

3.2.2 Magnetizing curve

When the machine runs at synchronous speed (1500rpm), the rotor and load parameters of the equivalent circuit can be ignored as the slip is zero. Therefore, the magnetising curve of the machine can be obtained by varying the supply voltage and measuring the stator current. The recorded magnetising current when varying the supply voltage is shown in Fig. 5.

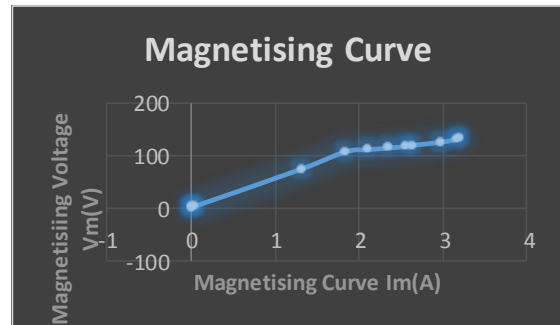


Fig. 6: The magnetising characteristics.

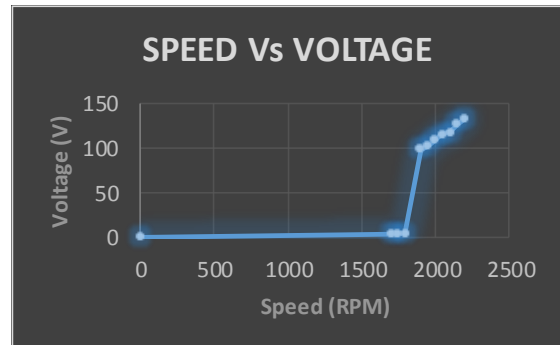


Fig.7: Voltage increase when speed is increased

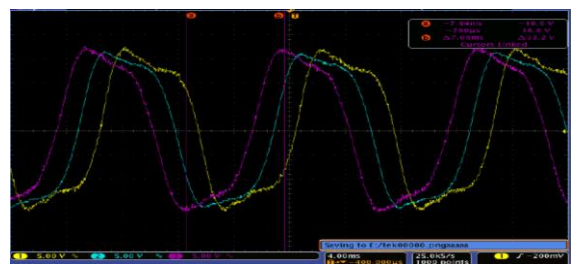


Fig. 8: 3-phase voltages of one group of nine phases with 40° phase shift

4. CONCLUSION

Nine-phase self-excited induction generator is analyzed using a Mathematical model Nodal admittance inspection method derived from the equivalent circuit of a NPSEIG. This method is developed for computer simulation to determine the necessary capacitance and VAR requirement to maintain constant terminal voltage for different constant speeds. Experimental results were conducted and some show that Speed is directly proportional to Voltage generated connected to a $40\mu F$ capacitor bank. Experimental results have evidenced that the process of voltage build up can be possible with zero excitation current as long as there is residual magnetism in the rotor core. Performance of the nine-phase induction generator under load and transient conditions will be presented in subsequent paper.

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