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Transient Analysis of a Multi-phase Induction Machine Operating as Generator

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Abstract

Multi-phase machines are considered serious contenders as compared to the three phase machines for variable applications in generating mode. This paper presents the transient performance analysis of a multi-phase induction machine operating in six-phase mode for power generation. In this paper the simulation and experimental analysis of a six-phase machine in generating mode have been made. The simulations are made and the machine functionality was investigated during no-load and when subjected to different types of loads. Experimental results are provided to confirm the ability of these models to represent during no load as well as during load period and the result were found to be satisfactory for power generation.

***Keywords**: Multi-phase, self-excited, Induction generator, transient*

1. Introduction

The increasing concern of the environment, especially the greenhouse effects, has motivated the world towards exploring the use of renewable energy sources and reduces dependency on fossil fuels. Most of the renewable energy sources, such as wind, mini-hydro, etc. are usually available in remote areas. A self-excited induction generator is found to be very suitable to generate electrical power in remote areas from renewable energy sources, such as wind and mini-hydro turbines [1]. A SEIG has many advantageous features over its counterpart synchronous generator. These features are low cost, high reliability, maintenance and operational simplicity, rugged construction, brushless operation, protection against overloads and short circuits, etc. Even though a SEIG is very suitable for wind and mini-hydro plants, it can also efficiently be used with prime movers driven by other energy sources, such as diesel, biogas, natural gas, gasoline, etc.In comparison with three phase machines, multiphase machines are considered as an alternative for variable speed applications. As there is a increase in demand of energy demand during the last few decades, the use of renewable energy sources has become essential and as a result of this, the investigation of the self-excited induction generator has gained importance as it is particularly for renewable power generation applications [2, 3, 4]. The application of self-excited induction generator due to its decreased unit cost, simple to operate and ease in maintaining is most suited in renewable energy systems. The advantages of self excited induction generator are no separate source for excitation is required, protection from overload, good transient performance, simple and robust construction and ease in maintenance. As the rating of power is increased and high reliability requirements, research in the area of multi-phase machines [2, 3, 4, 5] have been increasing.

In this paper the analytical and experimental analysis of a self excited induction generator operating in six phase mode has been carried out. The mathematical model is implemented in simulation platform for connection of pure resistive load, resistive-inductive load and resistive-inductive-capacitive load with certain value of capacitor that is connected across self excited induction generator operating in six phase mode. Experimentation is done on a prototype of six-phase induction generator made for the analysis to validate the results obtained in the simulation.

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2. Modeling of a Multi-Phase Self Excited Induction Generator

The schematic diagram of the basic two-pole six-phase induction generator is discussed in [5]. A Six phase induction generator consists of two stator winding sets namely abc and 123, whose magnetic axes are displaced by an arbitrary angle α. The windings of each three-phase set are uniformly distributed and have axes that are displaced 120^0apart. The three-phase rotor windings ar, br, cr as shown in Figure 1 are also sinusoidally distributed and has axes that are displaced by 120^0. The equations for the self excited induction generator operating in six phase mode, describes the behavior of a multi-phase machine, it is assumed that the neutral of both the stator winding sets are separate so that if a fault occurs in one set of the stator windings it does not propagate to the other set. The following voltage equations are written for a multi-phase induction machine as shown in equivalent circuit of the machine in Figure 2.

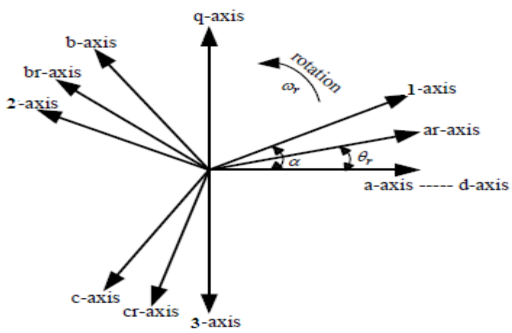


Figure 1. Phasor diagram representation of stator and rotor windings of six-phase induction generator

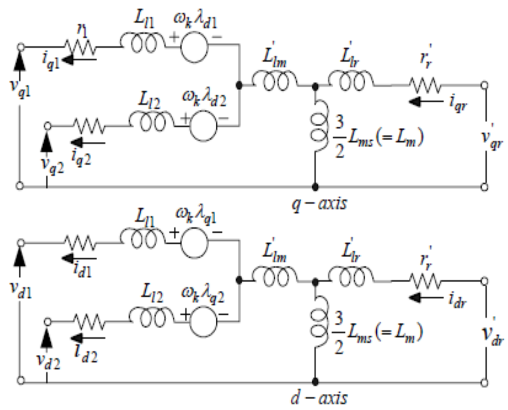


Figure 2. Circuit representation self excited induction generator in six phase operation

For the development of model of the six-phase machine operating in generating mode the differential equations are derived from the equivalent circuit of the machine. From the above equivalent circuit we get the equations [5] and the model was being simulated in Matlab/ Simulink platform.

3. Simulation Results and Discussions

The simulation model a six-phase self excited induction generator is shown in the Figure 3. The blocks made for the machine include six-phase machine block, magnetic induction block, torque block and the load block [6, 7]. The dynamic response of the system is analyzed in MATLAB platform when the machine is at no load condition and when subjected to different types of loads. The data of the machine used for the simulation model are given in the Appendix.

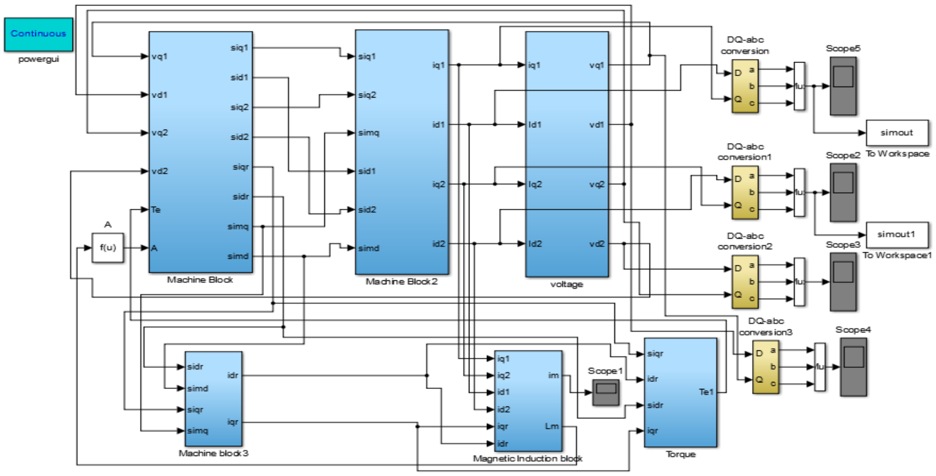


Figure 3. Simulation model of six-phase induction generator

3.1. Voltage and Current Characteristics when Excited by Capacitance under No Load Condition

Figure 4.shows the voltage build up of the induction machine under no load condition when the machine is excited by excitation capacitances values. The machine is excited by 41μF. It is observed that the magnitude voltage and current rise from their initial small values of voltage and currents to the steady state voltage and current. The excitation current is depicted in the figure and it is observed that the magnitude of current increases with the increase in capacitance values.

3.2. Voltage and Current Characteristics when the Six-Phase Machine is subjected to Resistive Load

In this mode of operation, at time t = 0.3s the machine is loaded by a load of R = 200 ohm with a c-bank connected across both the three-phase winding sets abc and 123 respectively. The results are shown in Figure 5. The terminal voltage has decreased from 240 volts to 200 when the machine is subjected to load at 0.3 seconds. The effect of the decrease in terminal voltage will cause a decrease in the capacitor current; this further affects the voltage regulation of the generator.

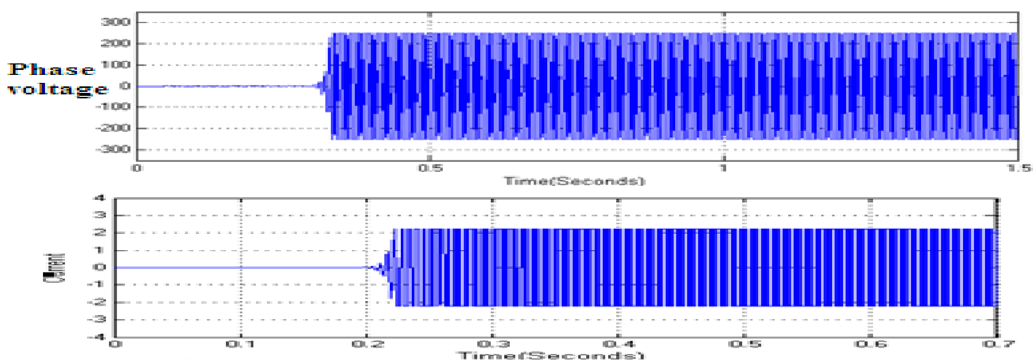


Figure 4. Phase voltage and current at both the sets of the machine during no load condition

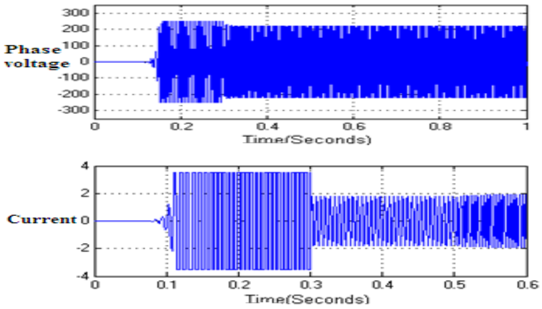


Figure 5. Phase voltage and current at both the sets of the machine during resistive load condition

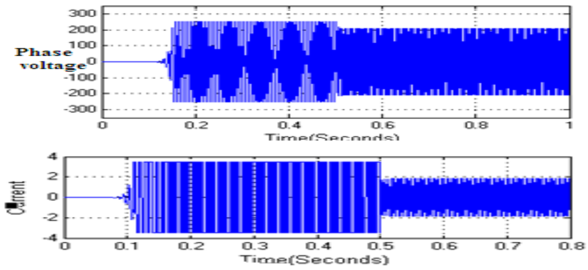


Figure 6. Phase voltage and current at both the sets of the machine during resistive inductive load condition

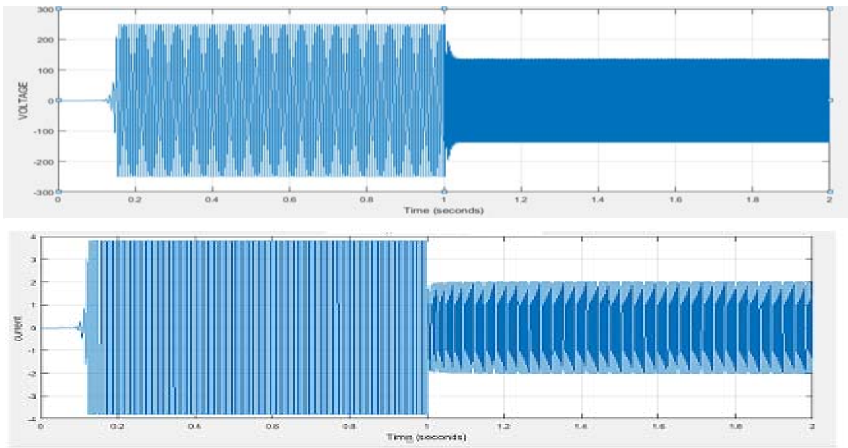


Figure 7. Phase voltage and current at both the sets of the machine during resistive inductive load condition

3.3. Voltage and Current Characteristics when the Six-Phase Machine is Subjected to Resistive-Inductive Load

At t = 0 s, a shunt capacitor with capacitance 41μF is connected across both the winding terminals of the induction generator without any load, and voltage is generated. The load is switched on at t = 0.22 s. It is observed that the terminal voltage is reduced by bigger value. RL loading operation causes a poor voltage characteristic of the SPSEIG. This is due to the main disadvantage of this generator and can be explained as resulting from under excitation of the machine.

3.4. Voltage and Current Characteristics when the Six-Phase Machine is Subjected to Resistive-Inductive-Capacitive Load

The transient response of the SPSEIG is feeding an RLC load (200 ohm. 08H, 12μF) as shown. The load is switched on at *t* = 1s. It is observed from the results shown that the terminal voltage and current attain their new steady-state operation, but with a slight reduction of output voltage. The effect of the RLC load on the SPSEIG output voltage can be compensated using a series (and/or parallel) capacitor. However, it can be seen that for the RLC load used in the test, the SPSEIG output voltage is still considerably affected by the connection of the load.

4. Experimental Set Up of Six-Phase Induction Machine Operating in Generating Mode

In order to validate the results obtained from the simulated system a prototype of six-phase machine set up was made. A three phase induction machine which consists of thirty six slots, 2.9A, 415volts, 1 Kw squirrel cage machine was used. The seventy two terminals of stator were taken out of the machine in order to test the machine for six-phase operation and loading test to be performed in the machine. The multi-phase machine was connected to a DC motor which acts as a prime mover which is rotating at 1000 rpm. At first the self excitation phenomenon of multi-phase induction generator was analyzed by plotting the magnetization characteristics. The magnetization curve shows the intersection of the no load terminal voltage with the capacitor load line. At no-load, the capacitor current Ic = V/Xc must be equal to the magnetizing current Im=V/Xm. The voltage is a function of Im, linearly rising until the saturation point of the magnetic core is reached. The output frequency of the self-excited generator is, f=1/(2πCXm) and ω=2πf where C is self-exciting capacitance.

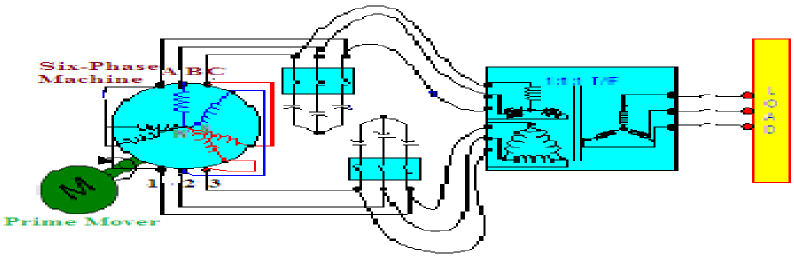


Figure 8. Multi-phase induction generator connected to the excitation capacitors and transformer

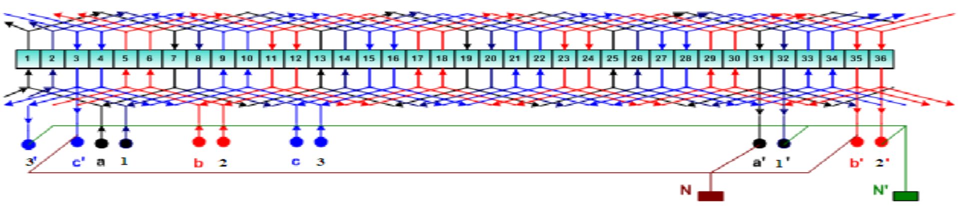


Figure 9. Winding pattern of a six-phase induction generator

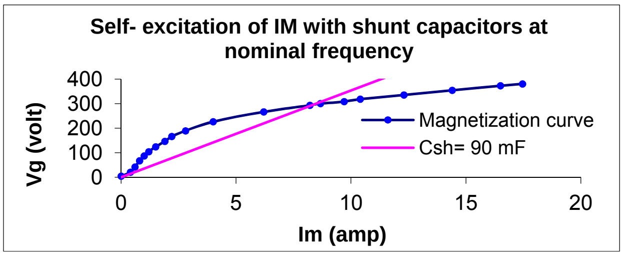
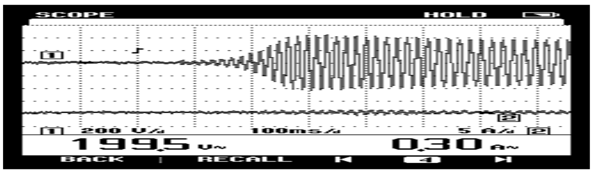


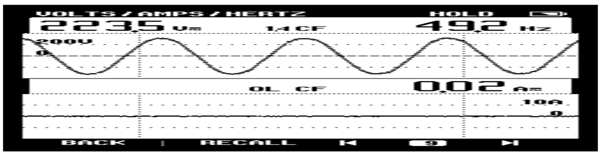
Figure 10. Magnetization curve of a six-phase induction generator

4.1 Self Excitation Transients of Six-Phase Induction Generator

To demonstrate the voltage and current transient during the analysis during no load condition at first excitation is being provided to the set abc by connecting a delta connected capacitor bank of 38 microfarad to one of the two stator sets and the machine is driven at 1000 rpm by a prime mover and the voltage and current transients are observed and in the second case the excitation capacitor bank is connected to the 123 set and the voltage and current transient are observed [8, 9]. The steady state voltage and current waveforms of during excitation at either of the two sets have been analyzed which is as shown in Figure 11-13.



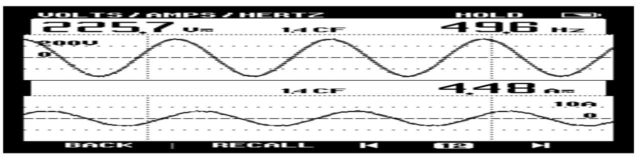
A



B

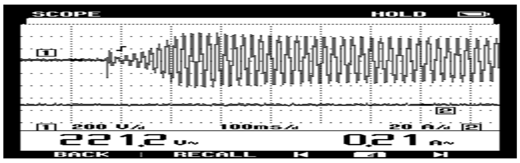
Figure 11. (A) Excitation at set abc, V/I transient at set 123 (B) steady state voltage & current waveform at set 123 when excitation at set abc

A



B

Figure 12. (A) Excitation at set abc, V/I transient at set abc (B) steady state voltage & current waveform at set abc when excitation at set abc



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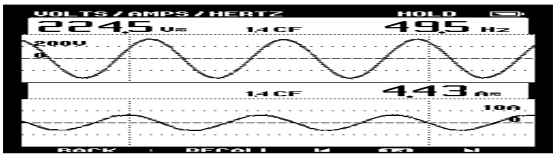

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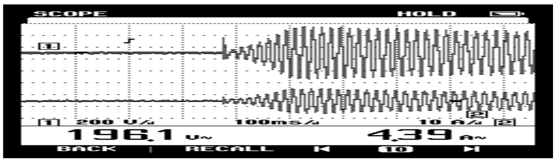

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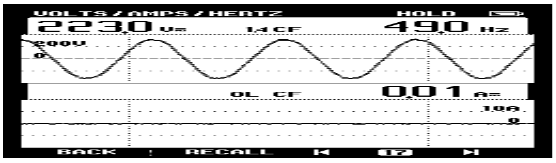
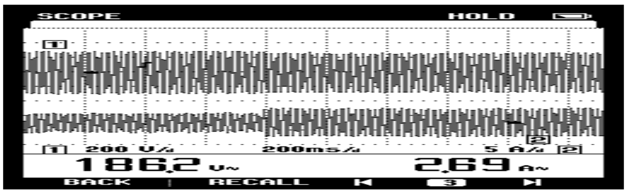


D

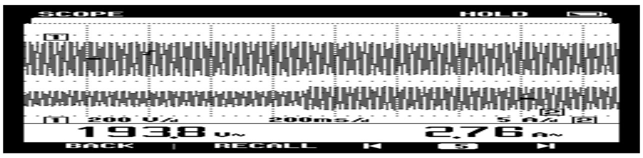
Figure 13. (A) Excitation at set 123, V/I transient at set abc (B) Excitation at set 123, V/I transient at set 123 (C) steady state voltage & current waveform at set 123 when excitation at set 123 (D) steady state voltage & current waveform at set abc when excitation at set 123

4.2 Loading Transients of the Six-Phase Induction Generator

During this analysis the six-phase induction machine is loaded and the transients are observed at the two stator sets. To find possibility of supplying two different loads from one six-phase machine, static three-phase star connected resistance load were connected to each three-phase winding set. The voltage and current waveforms of the sets abc and 123 for loading at one set and the transients at the other set have been analyzed as shown in Figures 14-17. It is found that loading at any of the two three-phase sets affects the voltage and current of both winding sets.



A



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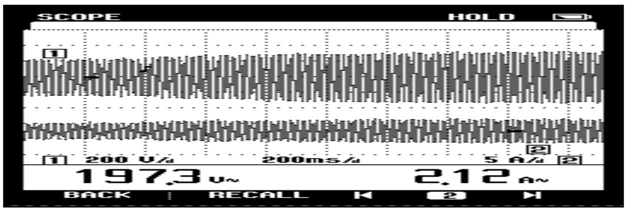


C

Figure 14. (A) Excitation at set abc, V/I transient at set abc when resistively loaded with loss of transformer input 123 (B) Excitation at set abc, V/I transient at set abc with loss of transformer input abc (C) Excitation at set abc, V/I transient at set abc for step unloading from transformer output

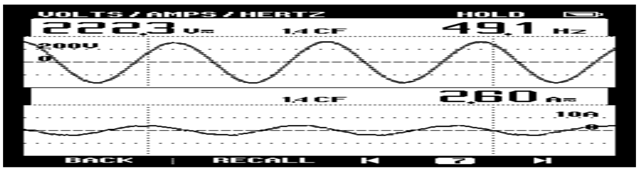
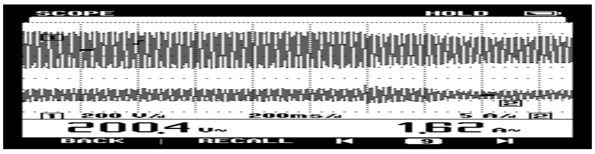


Figure 15. Steady state voltage & current waveform at set abc when excitation at set abc for a resistive load



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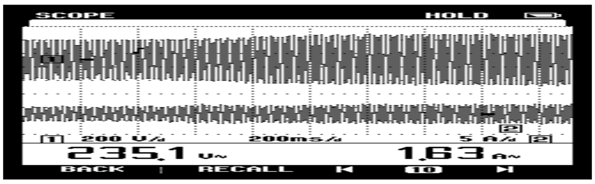

B

Figure 16. (A) Excitation at set abc, V/I transient at set 123 for step loading
(B) Excitation at set abc, V/I transient at set 123 during unloading

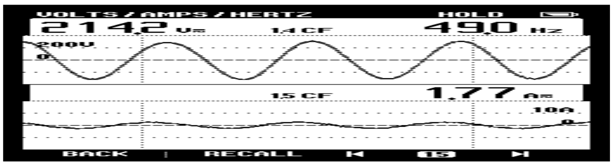

Figure 17. Steady state voltage & current waveform at set 123 when excitation at set abc for a resistive load

5. Conclusions

In this paper an analytical model of a six-phase induction generator have been modeled in which transient behavior of the machine when subjected to different types of loads have been analyzed. To demonstrate the ability of the six-phase machine to feed two different loads connected across its stator terminals experimental results have been presented. In the experimental analysis the voltage and current transient and steady state behavior of current have been analyzed during no load and loaded conditions when excitation is being provided to either of the two stator winding sets. It is found that the six-phase generator is capable of supplying to different loads connected across its stator terminals and can be excited without any problems using a 3-phase capacitor. It implies that loss of excitation at one of the three-phase sets can be sustained and operation undisrupted. Therefore a six-phase machine can be considered reliable as compared to three phase machines.

Appendix

The parameters of the six phase self-excited induction generator used in simulation are as follows: Resistances in the stator winding: $r_1 = r_2 = 1.8$ ohm,
Leakage inductances in the stator winding: $L_{l1} = L_{l2} = 0.0133$ H,

Resistance in the rotor winding: r_r = 2.2ohm,
Leakage inductance in the rotor winding: L_{lr} = 0.0133 H,
L_{lm}' = 0.0111 H,J = 0.03 Kg /m^2
a = 0.141, b = 0.001, c = -0.001, and d = 0.000050

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