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LOADING EFFECTS OF A CAPACITOR EXCITED INDUCTION GENERATOR

Rakgati E.T and Setlhaolo D.
University of Botswana
Faculty of Engineering and Technology
Rakgatie@mopipi.ub.bw, Setlhaolo@mopipi.ub.bw

ABSTRACT
In this paper, the design and loading effects of a capacitor excited Induction generator (CEIG) are considered with special attention to the excitation capacitance. An Induction machine can operate as a CEIG provided the induction machine is driven beyond synchronous speed by a prime mover and suitable excitation capacitance connected to its terminal. The design of the CEIG was based on a 7.5 kW induction motor mechanically coupled to a 20 kW DC generator. With the coupled machines, the design involved designing a suitable controller for the prime mover, determination of the induction machine parameters and the determination of the excitation capacitance.

The testing of the CEIG was done both on no load and at on load conditions. Under no load conditions, the terminal voltage of the generator was observed under different excitation capacitance and also with different prime mover speeds. The generator tests at load condition were carried out both for static and dynamic loads.

1. Introduction

It is well known that if an appropriate capacitor bank is connected at the stator terminals of an externally driven induction machine, a voltage is induced in the machine windings due to the excitation provided by the capacitor bank. The induced voltage would continue to rise until the reactive power supplied by the capacitor bank is balanced out by that required by the induction machine. For the excitation to take place two conditions (apart from the capacitor size) should be met; there has to be some remanent magnetism in the rotor bar and also the induction machine should be driven above synchronous speed by a prime mover. This results in an equilibrium state being reached and the machine now operates as a generator (self excited induction generator) at a voltage decided by the size of the excitation capacitor, speed of the prime mover, the parameters of the induction machine and also the parameters of the load.

The self excited induction generator did not find many practical applications, because of its inability to control the terminal voltage and frequency under varying load conditions. In recent years due to the increased emphasis on renewable energy resources development of suitable isolated power generators driven by energy sources such as wind, micro-hydro and biogas, has assumed greater significance. Because of its reduced unit cost, brushless rotor construction, absence of a separate source for excitation, ruggedness, and ease of maintenance, a capacitor excited induction generator has emerged as a suitable candidate for isolated power systems.

In this paper, the capacitor excited induction generator is designed based on the 7.5 kW Induction motor mechanically coupled to a 20 KW DC machine. The design involved designing and implementation of a suitable controller for the DC machine allowing for speed control. In addition to the controller, induction machine parameters and the excitation capacitances are determined. In verifying the CEIG tests were done both on no load and at on load conditions. Under no load conditions, the terminal voltage of the generator was observed under different excitation capacitance and also with different prime mover speeds. The generator tests at load condition were carried out both for resistive and inductive load.

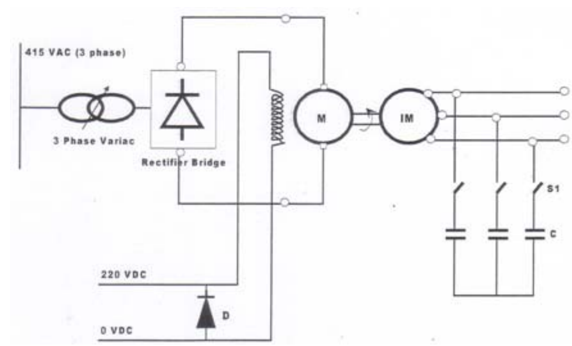

Figure 1. Experimental set up of the self excited Asynchronous generator

2. Design of Capacitor Excited Induction Generator

The Experimental set up of a CEIG is as shown in Figure 1. It can be observed from Figure 1 that the generator is made of three main components which are prime mover (DC motor), Induction machine and the excitation capacitance. The different components used for the designing of CEIG were based on the available 7.5 kW Induction motor coupled to a 20 KW DC motor. The design of the different components of the CEIG entails the following: designing a speed controller for the prime mover, determination of the equivalent circuit parameters of the three phase induction motor and the determination of the excitation capacitor value to be placed across the terminals of the induction machine.

2.1 DC motor

The speed of a DC motor can be controlled by varying the supply voltage as given by equation 2.1.

$$\omega = \frac{V_a - i_a R_a}{K\Phi} \tag{2.1}$$

where V_a, i_a, R_a, $K\Phi$ is armature supply voltage, armature current, armature resistance and field flux constant respectively.

The DC motor used for this particular application is of the separately excited type with separate supplies for the field and the armature windings. The variable armature winding supply was derived from the combination of a three-phase rectifier bridge with a variable AC supply as shown in figure1. The rectifier bridge was chosen so as to withstand the rated conditions of the DC motor. The field voltage of the motor was supplied directly from a 220 V DC supply.

2.2 Induction Motor

The specifications of the induction motor used are as follows: 400 V, 7.5 kW, 4 pole and power factor of 0.83. The analysis of the induction motor can be simplified by representing the machine by a per phase equivalent circuit diagram as shown in Figure 2. The determination of the equivalent circuit parameters of the machine was carried out by the well known methods which involve direct current, no load and block rotor tests. The determined equivalent circuit parameters of the induction motor are R_1=2.10Ω, X_1= X_2'=6.12Ω, R_c=1920.8Ω, X_m = 95.74Ω and R_2'=2.23Ω.

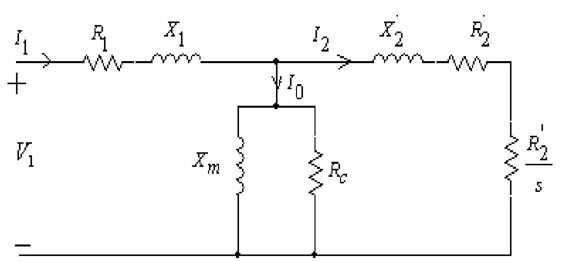

Figure 2. Per phase equivalent circuit of induction. Motor

2.3 Capacitor Value

A review of the literature reveals three approaches for the steady state analysis of the self excited induction generator which are; loop impedance, nodal impedance [1,2] and d-q axis model methods [3] based on the generalized machine theory [4]. But in this paper, the excitation capacitor value was determined from the comparison of magnetization curve of the induction motor and the capacitor volt ampere characteristic. The point of intersection between the magnetization curve and the capacitor volt-ampere characteristic represents a condition of stable self excitation and defines the corresponding no-load terminal voltage and exciting current [2,5]. The magnetization curve for the particular motor and the capacitor volt-ampere curve are as shown in Figure 3. The point of intersection of the two graphs corresponds to a current of 7.20A. A delta connected induction motor was used for this investigation as such the phase current is 4.16 A$\left(7.2/\sqrt{3}\right)$.

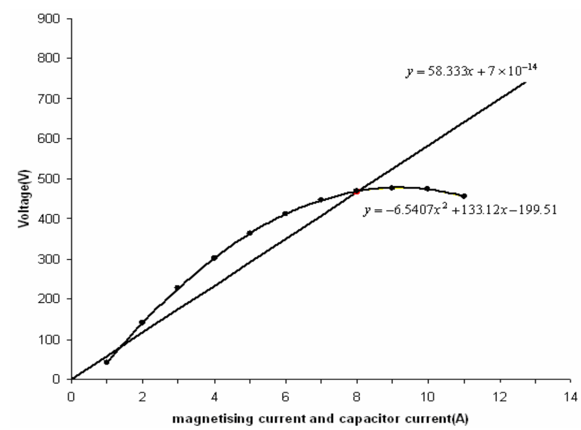

Figure 3. Magnetization voltage versus Magnetization current for the motor

The capacitor value per phase for a delta connected capacitor bank allowing for 420 V generator output is given by equation 2.2.

$$\begin{aligned} X_c &= \frac{V_{ph}}{I_{ph}} = \frac{1}{2\pi f} \\ \Leftrightarrow C &= \frac{I_{ph}}{2\pi f V_{ph}} = \frac{4.16}{2\times\pi\times50\times420} = 32\,\mu F \end{aligned} \tag{2.2}$$

In this investigation, the available capacitors were of a maximum voltage rating of 300 V so as such not able to withstand the 420 V. The above problem was arrested by replacing the delta connected capacitor bank with a star arrangement. The capacitor value per phase for the star connection was calculated to be 96 µF and the actual value used for the investigation was 100 µF so as to cater for the stator leakage reactance.

The verification of the capacitor value required for excitation was done by using the approximate equivalent circuit of CEIG as shown by Figure 4.The excitation capacitance should be able to satisfy the reactive power requirements of the magnetizing branch (X_m). The capacitance required, assuming line to line voltage of 420

V is given by equation 2.3

$$\frac{420}{X_m} = \frac{420}{X_c} \qquad (2.3)$$

$$\Leftrightarrow C = \frac{420}{420 * 2\pi * 50 * 95.74} = 33\mu F$$

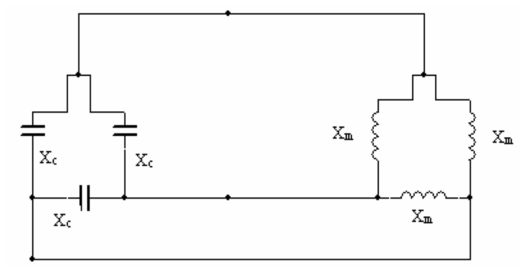

Figure 4. Approximate equivalent circuit of CEIG

Calculated capacitor value from the above method corresponds to the one calculated from the magnetization curve.

3. No load test of CEIG

The no load test of the CEIG involves driving the generator with a prime mover and observing the magnitude of the terminal voltage at different prime mover speeds and also at different excitation capacitor sizes. For the investigation one factor (capacitor value or prime mover speed) was varied at a time.

3.1 Effect of capacitor value

For this investigation a manual switched capacitance was used, with the prime mover operated at a constant speed and the terminal voltage observed as a function of capacitance. The above investigation was repeated for different prime mover speeds. The results are as shown in Figure 5. The following observations can be made: terminal voltage increases with an increase in the capacitor value, the minimum excitation capacitor value decreases with the prime mover speed and the same excitation capacitor value yields a higher terminal voltage at a higher prime mover speed. The above-mentioned observations can be explained by referring to the magnetization curve of the machine. With the same prime mover speed and different excitation capacitance, the intersection of the capacitor volt-ampere characteristic line and the magnetization curve shifts up and down for a higher and lower capacitor value respectively. The effect of different prime mover speeds can be explained by considering the fact that the prime mover speed shifts the magnetization curve to the left and right for higher and lower speeds respectively [1,6].

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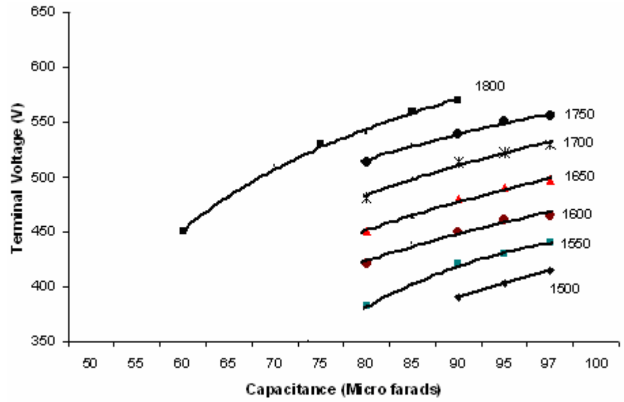

Figure 5. Variation of terminal voltage with excitation capacitance for different prime mover speeds.

3.2 Effect of prime mover speed

For this investigation, the terminal voltage was observed at different prime mover speeds but with the same capacitor value (100 µF*)* and the results are as shown in Figure 6. The observation from Figure 6 is that, the terminal voltage increases with an increase with the prime mover speed. This is due to the fact that the magnetization curve shifts [7] as a function of prime mover speed as explained in the previous section.

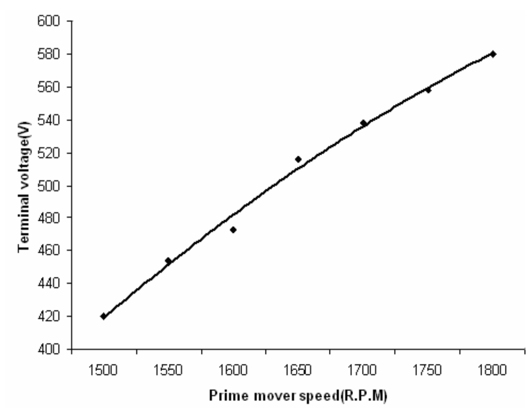

Figure 6. Variation of prime mover speed with terminal voltage under the same capacitance

4. Load test of CEIG

In addition to the no load test the CEIG was also investigated under load condition. The different loads considered in the investigation are: resistive, inductive and a combination of resistive and inductive loads. The terminal voltage was allowed to build up before the load was connected and observed as a function of the load. In addition to the different loads mentioned above, the CEIG was also with an induction motor acting as a load.

4.1 Resistive load

For these investigations a switched three phase resistive bank was used, the terminal voltage and the power consumed for different resistive values were observed for different prime mover speeds and the results are as shown in Figure 7.

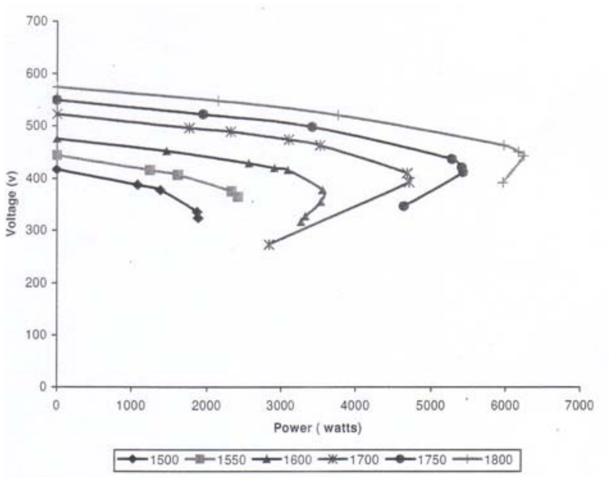

Figure 7. Variation of terminal voltage for Resistive load

It was also observed that the speed drops when the load is switched on. The drop in speed was dependent on the load, the greater the load the greater the speed drop. Because the frequency output of the generator depends on the speed of the prime mover, for fixed speed operation the frequency varies with the load. In this particular investigation the speed was controlled by readjusting it to the set value by manually increasing the supply voltage of the prime mover. As suggested by [5], the frequency control could be achieved by employing a converter and inverter scheme. It is also noticeable that the terminal voltage of the generator drops with an increase in the resistive load [8,9].

It can be observed from Figure 7 that there is a certain value of maximum power which can be derived from the CEIG having a fixed terminal capacitance. The maximum power output increases with the prime mover speed. Another observation which was made about the CEIG is that it has a poor voltage regulation [1,2,4,6]. Poor voltage regulation in this investigation was tackled by switching extra capacitance as a function of load to maintain a constant terminal voltage. A smooth variation of the capacitance can be obtained by the use of a static exciter employing a fixed capacitor – thyristor controlled reactor scheme [5,6].

4.2 Inductive Load

The same investigation as that of the resistive load was done for the inductive load, i.e. switching on the inductive load with the terminal voltage kept constant by switching in extra capacitance. Unlike the resistive loads, inductive loads consume reactive power which is supplied by the excitation capacitance. The variation of the reactive power as a function of excitation capacitance for constant terminal voltage is shown by Figure 8 below. It is noticeable from the figure that the excitation capacitance increases with an increase in reactive power. This is due to the fact that the capacitance provides reactive power for both the CEIG and the load. In balancing out the reactive power requirements of the CEIG, more excitation capacitance is required to cater for an increase in inductive loads.

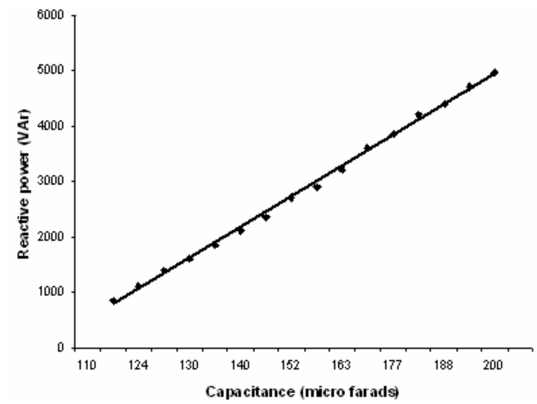

Figure 8. Variation of reactive power with capacitance for speed of 1500 rpm

4.3 Combination of Resistive – Inductive Loads

For this investigation, different combinations of parallel R – L loads were used. Just like for the previous loads, the load was connected with its corresponding capacitance to maintain constant terminal voltage. The active power vs. reactive power for the different combinations of the R – L loads are as shown in Figure 9 under different excitation capacitance. It is noticeable from the figure that for variable R-L loads of variable power factor, the size of the excitation capacitance is affected by the fact that as the power factor is decreased, the load current becomes more inductive and as such more capacitance is required to offset this inductive component.

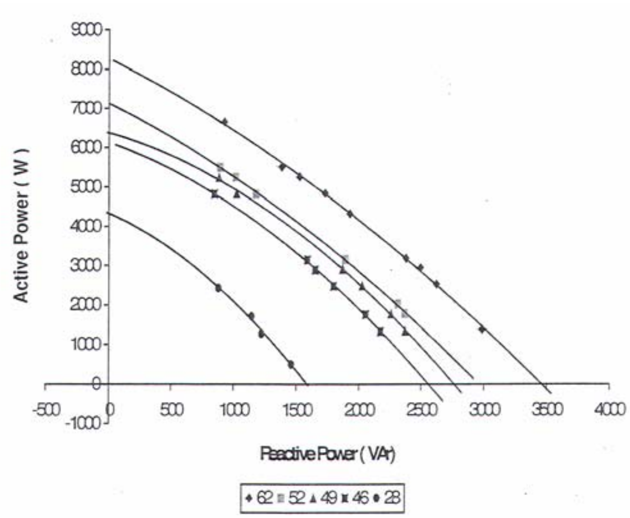

Figure 9. P-Q diagram for different μF capacitance values

5. Conclusion

The following conclusions are drawn on the loading performance of the capacitor excited induction generator:

The use of the intersection of the magnetization curve and the capacitor volt-ampere characteristic to calculate the excitation capacitance has yielded accurate results. The calculated excitation capacitance value has been verified by the use of the approximate equivalent circuit of the Capacitor excited induction generator.

The terminal voltage output of the generator is directly proportional to both the value of the excitation capacitance and the prime mover speed provided the capacitor value is greater than the minimum excitation capacitance.

The terminal voltage and the frequency output of the generator vary with an increase in load. It has been shown that the terminal voltage variation can be successfully eliminated by an addition of extra capacitance as the load increases.

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