

INDUCTION GENERATOR FOR MICRO-HYDRO APPLICATIONS

By

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Abstract

In developing countries, there is a growing interest in micro-hydro schemes to provide electric power to remote villages. It is common practice to provide a single-phase output from a three-phase induction generator, with capacitors to minimize the unbalance. In the implementation stage, rules of thumbs are used to determine the value of the excitation capacitor. This results in the machine operating with unbalance. This paper attempts to develop an analytical method to design such schemes.

A mathematical model was developed to represent the generator with single phase loading under minimum unbalance. The model has been experimentally validated. Criteria were developed to determine the best value of the excitation capacitor which gives the required terminal voltage and unbalanced operation of the machine. A case study illustrates the application of this model to design a 0.9 kW micro-hydro scheme in Sri Lanka. This project has been implemented and successfully operated since January.

1.0 List of Symbols

R_s, X_s	p.u. stator resistance and reactance at the base frequency
R_r, X_r	p.u. rotor resistance and reactance at the base frequency
X_m	p.u. magnetizing reactance at the base frequency
Z_r, Z_s, Z_m	p.u. rotor, stator and magnetizing impedance
Z_{max}	p.u. per phase impedance of the machine
R_L, X_L, Z_L	p.u. load resistance, reactance and impedance
V_g	p.u. air-gap voltage
f	p.u. generated frequency
u	p.u. speed of the generator

2.0 Introduction

In developing countries, there is much interest in micro-hydro projects mainly for village electrification. These small generating plants supply power in remote locations where utility power is far from reach. Due to advantages such as availability, cost-effectiveness and robustness induction generators are commonly used in such schemes. Furthermore, in order to reduce the capital cost, crude voltage and frequency control techniques are used for these machines. The value of the excitation capacitor is chosen so as to obtain the rated voltage and the rated frequency at the full load condition. The voltage and the frequency are maintained at their rated values by connecting a resistive ballast which maintains the sum of the consumer load and the ballast load at the rated full load of the generator, under all operating conditions. A detailed description of the system used for micro-hydro plants can be found in [1], [2].

Since consumer loads connected to the micro-hydro schemes are generally single-phase lighting loads, generators with single-phase output are used in these schemes. With a three-phase generator, since loading on each phase could vary from time to time, the ballast load would require more sophisticated controller. Also, the cost for distribution lines will be less with a single-phase output. However, a single-phase generator has a higher cost per kW when compared with a three-phase generator. Three-phase induction machine which is operating as a single-phase generator is therefore commonly used in such schemes. Reference [3] gives various ways an induction generator can be connected to a single-phase load with minimum unbalance. Analysis of the induction generator under single-phase loading with minimum unbalance using symmetrical component theory can be found in [3], [4] and [5].

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In most of the micro-hydro schemes, the value of the excitation capacitance and the rated power output of the generator are obtained using rule of thumbs. No analytical solutions are used. This paper attempts to develop an analytical method in the design of micro-hydro systems. As the induction generator is always operated with a ballast load, it could be designed to operate near the best operating point, which would provide maximum power output and minimum unbalance. Therefore, a model which gives accurate results near its balanced operating point would be sufficient. In this paper a simple model which is based on the same technique that is used for the three-phase operation of the induction generator [6] is presented. The model has been validated using laboratory experiments. A design criteria, using the model developed and using the known results, were developed to design micro-hydro schemes for given operating conditions. Finally a case study illustrates the application of the design criteria to design of a micro-hydro scheme.

3.0 Induction generator operating with a single-phase load

A three-phase generator can be converted to a single-phase generator which produces approximately 80% of the motor rating by connecting two capacitors as shown in Fig 1. In the figure the load represent the sum of the consumer load and the ballast load.

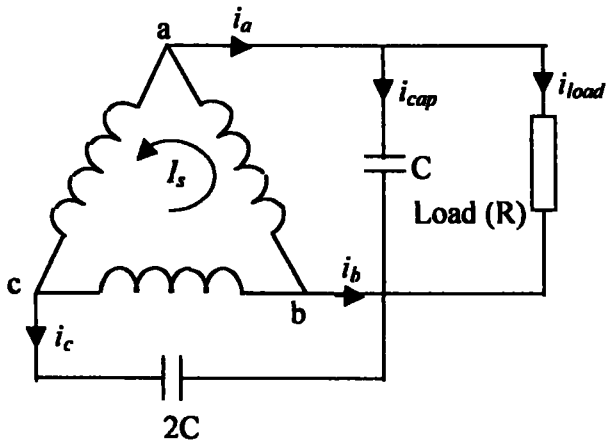


Fig 1. Schematic of the single-phase connection

In the analysis of the above circuit it is assumed that the load connected is always equal to the load corresponding to the balanced operation of the generator and is resistive. Reference [3], shows that in order to have balanced operation, the current through the load and the excitation capacitor should have the following relationship.

$$i_{load} = \sqrt{3} i_{cap} \quad (1)$$

The other currents have the following relationships.

$$i_a = i_{load} + i_{cap} \quad (2)$$

$$i_b = i_a - i_c \quad (3)$$

$$|i_c| = 2 |i_{cap}| \quad (4)$$

The phasor diagram showing the line current for each phase- at the balanced operating condition is shown in Fig 2.

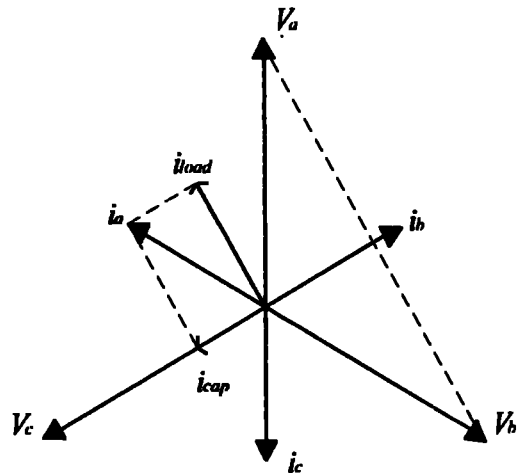


Fig 2. Phasor diagram for correct single-phase connection

From Fig 2, it is clear that even though the generator is connected to a single-phase load, the three line currents are balanced. When an induction generator is used in this manner, the correct connection of the capacitor 2C must be ensured. If the capacitor 2C is connected between phases a and c instead of c and b, then the resultant phasor diagram would be as shown in Fig 3.

In this case, the generator will run as an unbalanced system with 'a' phase line current nearly zero. Therefore, for the balanced operation of the induction generator correct connection of the capacitor 2C is essential.

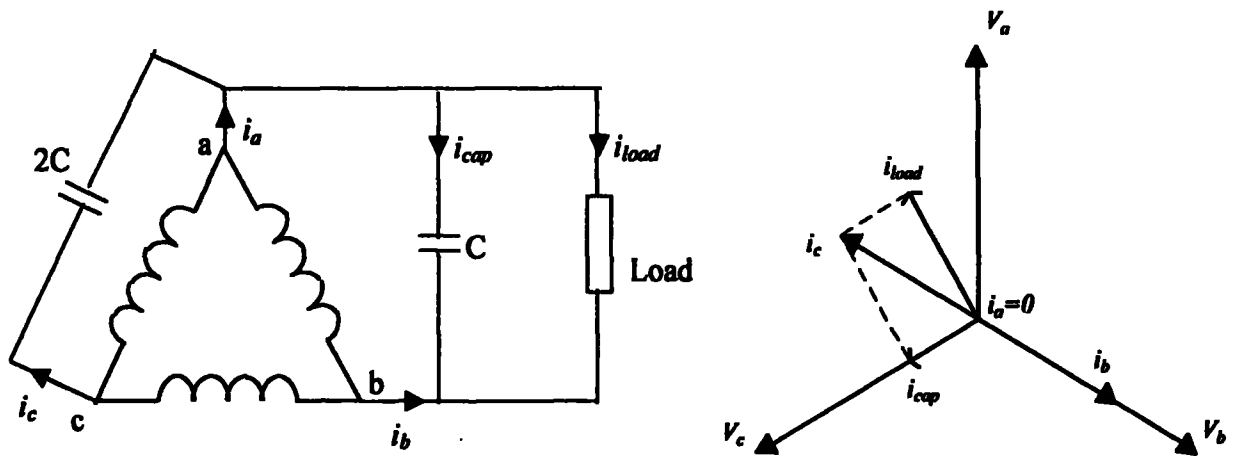


Fig 3. Schematic and the phasor diagram for the wrong connection

4.0 Analysis of the induction generator operating with a single-phase load

Conventional machine analysis is not helpful in the study of the variation of the generator voltage and its frequency with changes of load. A mathematical model is required to represent the induction generator under different operating conditions.

In the equivalent circuit shown in Fig 1, each phase of the induction generator can be represented by the circuit shown in Fig 4 [4].

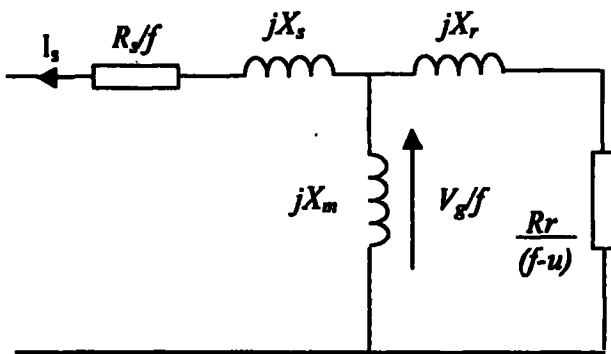


Fig. 4. Equivalent circuit of the induction generator

From Fig 4:

Rotor impedance

$$Z_r = \frac{R_r}{(f-u)} + jX_r \quad (5)$$

Stator impedance

$$Z_s = \frac{R_r}{f} + jX_s \quad (6)$$

Magnetizing impedance

$$Z_m = jX_m \quad (7)$$

Machine impedance

$$Z_{\text{mac}} = X_s + \frac{Z_r Z_m}{Z_r + Z_m} \quad (8)$$

From Fig 1:

Impedance of the capacitor, C

$$Z_{\text{cap1}} = \frac{-j}{\omega C} \quad (9)$$

Impedance of the capacitor, 2C

$$Z_{\text{cap2}} = \frac{-j}{2\omega C} \quad (10)$$

For the general case:

Load impedance

$$Z_L = R_L + jX_L \quad (11)$$

From Fig 1:

$$I_s Z_{\text{loop}} = 0 \quad (12)$$

Where Z_{loop} is the loop impedance of the delta-connected machine, given by:

$$Z_{loop} = \frac{Z_{nnc} Z_{cp1} Z_L}{Z_{nnc} Z_{cp1} + Z_{nnc} Z_L + Z_{cp1} Z_L} \quad (13)$$

$$+ \frac{Z_{nnc} Z_{cp2}}{Z_{nnc} Z_{cp2}} + Z_{nnc}$$

At the steady-state self-excitation with balanced operating condition, since there are no negative sequence components $I_s \neq 0$. Therefore

$$Z_{loop} = 0 \quad (14)$$

Self-excitation would occur, if any one of the roots of (14) has a positive real part [7]. In this equation, both the steady-state value of X_m and operating frequency (f) are unknowns for given value of self-excitation capacitance and speed. The above equation can be solved using a technique similar to that described in [8]. A MATLAB routine which uses the function 'constr' for multi-variable constraint minimization was written to find the solution.

After calculating the steady state frequency and X_m , the next step is to obtain the air-gap voltage, V_x corresponding to X_m . This can be obtained by running the induction machine with zero slip. In this case, $R/(f - \omega)$ term becomes infinite and the stator quantities can be neglected when compared to X_m . Therefore, by measuring the input voltage and the input current a relationship between V_x/f and X_m can be obtained.

Once the operating frequency and the air-gap voltage corresponding to X_m is obtained, the stator current, the load current and the terminal voltage can be obtained using circuit theory and using the equivalent circuit of the induction generator under balanced operating conditions [3].

5.0 Validation of the mathematical model

A 240/415 V (Δ/Y), 5.2/3 A, 1.1 kW, 1420 rev/min induction machine was used to validate the mathematical model. The data for the induction machine is given in Appendix A. For the induction machine, the relationship between V_x/f and X_m was obtained by running the machine at zero slip. A 30 μ F capacitor was used to self-excite the generator and using a lamp load the terminal voltage and the current through each phase of the induction generator were obtained by experiment. The terminal voltage of the induction generator was also obtained using the mathematical model.

The above experimental results as well as those obtained using the mathematical model are shown in Fig 5. Fig 5(a) shows the variation of the terminal voltage with load for a purely resistive load and Fig 5(b) shows the current in each phase of the machine obtained experimentally and the balanced three-phase current obtained using the mathematical model.

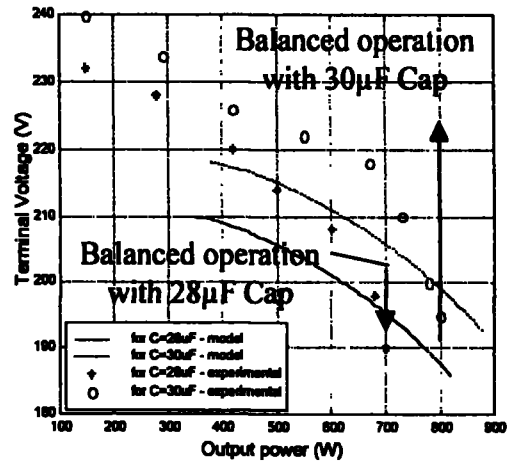


Fig 5(a). Generated voltage

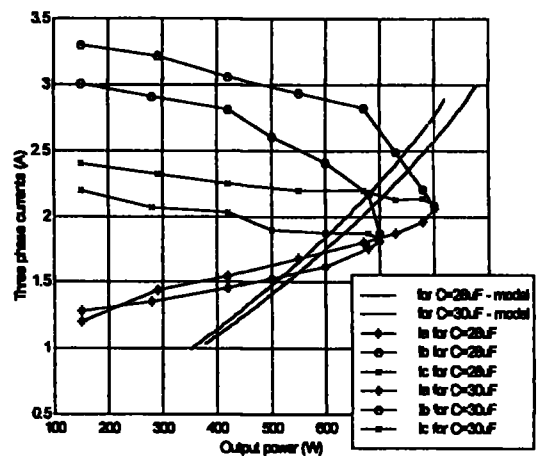


Fig 5(b). Current in each phase

Substantial agreement between the experimental results and those obtained using the mathematical model near the balanced operating point of the induction generator is observed. The discrepancies in the results were due to (a) the assumptions listed below, inherent in the mathematical model, (b) the errors in the measurement of the resistances and reactances used in the mathematical model and (c) errors in measuring the voltages and currents. The following assumptions were made in the derivation of the mathematical model:

- (a) Except the magnetizing reactance, all other quantities were assumed to be not affected by the magnetic saturation.
- (b) Leakage reactances of the stator and the rotor were taken to be equal.
- (c) Core losses were neglected.
- (d) MMF space harmonics and the time harmonics of the induced voltage and current were ignored.

When the machine is operating in the unbalanced region, all the voltages and currents would be non-sinusoidal, thus measuring errors would be significant. Further, the mathematical model would not give accurate results due to the presence of negative sequence components.

Since the operation of the machine near its balanced operating point is the only interesting region for micro-hydro applications, this model can be used for further studies.

6.0 Design criteria

The above model could be used to design a micro-hydro scheme by taking into account the following constraints:

- (a) Three-phase currents of the induction machine should be balanced and less than the rated current of the machine.
- (b) Generated voltage should be at least 220 V.

The mathematical model was used to study the operation of the induction generator near operating point, which gives minimum unbalance with different values of excitation capacitors. According to equation (1), in order to run the machine with single-phase load with minimum unbalance, the power output of the generator and the value of the excitation capacitor (C) connected across the load should have the following relationship:

$$\text{Output power of the generator} = \sqrt{3} V^2 \sin \alpha \quad (15)$$

From the mathematical model and using (15), the terminal voltage corresponding to a given output power could be obtained for different values of excitation capacitance. Intersection of the terminal voltage characteristics obtained using the mathematical model and that obtained using (15) gives the operating point of the machine under minimum un-balance.

7.0 Case study

The above design criteria was used to design a micro-hydro scheme using the same generator given in Appendix A. Fig 6(a) shows the variation of the terminal voltage obtained using the mathematical model and using (15). Corresponding balanced three-phase winding current is given in Fig 6(b).

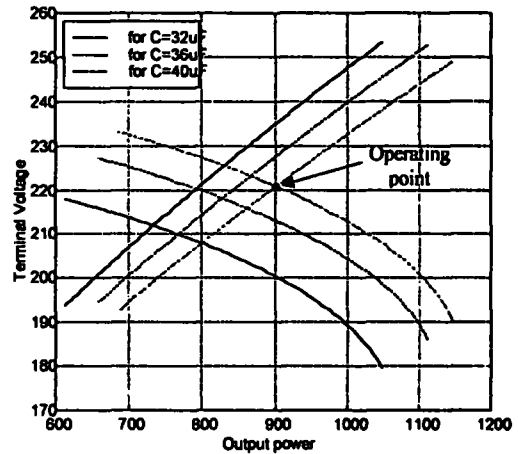


Fig 6(a). Generated voltage from the mathematical model and from above (15)

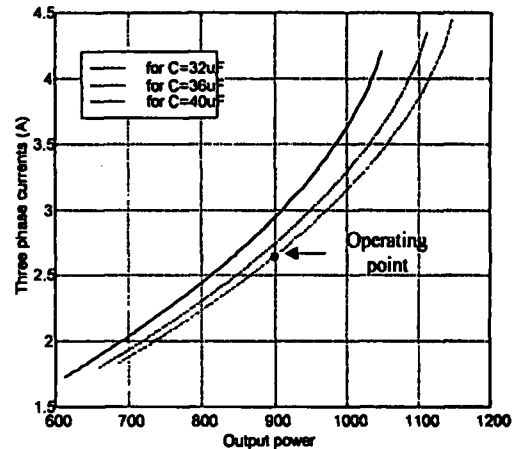


Fig 6(b). Balanced three-phase current

From Fig 6(a) it is seen that the generator can produce 220V at 900W output power (81.8% of the power corresponds to the motoring operation) if the excitation capacitor is 40μF. Fig 6(b) shows that under this condition, the phase current of the generator is well below its rated current.

9.0 Appendix A

Machine is Δ connected.

$V_{base} = 240 \text{ V}$, $I_{base} = 3.0 \text{ A}$ and $Z_{base} = 80 \Omega$

Rotor resistance = 0.0663 p.u.

Stator resistance = 0.08625 p.u.

Stator leakage reactance = 0.1015 p.u.

Rotor leakage reactance = 0.1015 p.u.

Magnetizing curve



Fig. 8. Magnetizing curve

10.0 Acknowledgement

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11.0 Reference

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