CAPACITIVE - BALLAST BASED INDUCTION GENERATORS FOR SMALL - HYDRO SCHEMES

by

D. B. Ekanayake, J. B. Ekanayake

Abstract

It is now recognized that small-hydro plants especially of the run-of-river type can be considered as a sustainable electricity generation option. However, sustainability of such plant will also depend on the robustness and economics of the generator and the associated control and protection circuitry. Induction generators are extensively used for micro-hydro plants (tens of kW to a few hundred kW) whereas for mini-hydro plants (1 - 50 MW) synchronous machines are employed. Due to the requirement of large resistive ballast, induction machines cannot be employed for mini-hydro applications. This Paper presents an induction generator based on a switched capacitor ballast that can produce a single-phase output while maintaining balanced three-phase currents in the machine. The operating principle is discussed and simulation and experimental results are used to validate the novel scheme.

1.0 Introduction

An induction generator, i.e. an induction motor with excitation capacitors, is considered to be a cheap and robust source of power for small-hydro-generating plants. These small generating plants can be used as a village micro-hydro-plant or as a mini-hydro-plant supplying power to isolated industrial loads such as tea factories or one that is connected to the national grid.

Existing micro-hydro schemes operate with nearly constant generated voltage by maintaining constant power output using an electronically controlled resistive ballast [1]. An application of a controllable capacitor ballast to maintain a constant voltage is presented in [2]. These schemes, employing both a resistive ballast and variable capacitive ballast, are controlled to maintain the generated voltage near its rated value but no concern has been given for the balanced operation of the machine which determines its operating life.

Mini-hydro schemes utilize synchronous machines and a governor controlled inlet valve is used to match the input power to the output power. The initial cost of these schemes is high due to the requirement of the excitation unit, the synchronization unit and the governor in addition to the cost of the actual machine. Further, a trained staff is required to maintain these plants. Usage of induction machines with resistive ballast for such schemes is not possible due to the requirement of high power ballast load.

In this Paper a capacitive-ballast based induction generator scheme is presented. If the scheme is used for a micro-hydro application then a run-of-river type scheme can be used at the expense of a small frequency deviation. If it is meant to be for a small mini-hydro scheme then a governor controller is required to balance the input and output powers. In order to minimize the initial cost of the distribution lines a single-phase power output can be used. In the proposed scheme, the ballast is designed not only to maintain the generated voltage near its rated value, but also to maintain balanced three-phase currents under single-phase loading from no load to full load of the generator.

2.0 Single-Phase Operation of the Three-Phase Generator

A three-phase generator can be converted into a single-phase generator that produces approximately 80% of the machine rating by connecting two capacitors as shown in Fig 1. The conditions for balanced operation can be expressed in terms of the currents as in equations (1) and (2) [3].

Manuscript received : 04.01.2003
Manuscript accepted : 13.05.2003

D. B. Ekanayake, B.Sc.Eng, Research Assistant, Department of Electrical and Electronic Engineering, University of Peradeniya.

Eng. (Dr.) J. B. Ekanayake, B.Sc.Eng, PhD, SMIEEE, MIE(SL), CEng, Senior Lecturer, Department of Electrical and Electronic Engineering, University of Peradeniya.

$$\left|\bar{i}_c\right| = 2\left|\bar{i}_{capl}\right| \quad (1)$$

$$\left|\bar{i}_{load}\right| = \sqrt{3}\left|\bar{i}_{capl}\right| \quad (2)$$

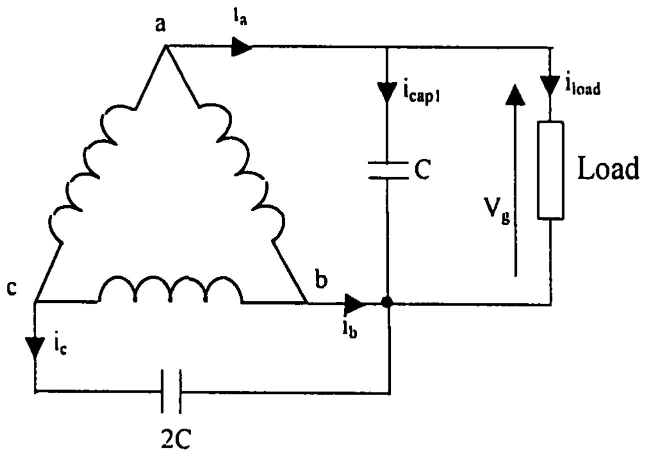

Fig 1: Single-phase output from a three-phase induction generator

In order to analyse the ballast-free controller of the induction generator the conditions for balanced operation are expressed using the fundamentals of load compensation described in [4]. The external components of the induction generator having a single-phase load and a three-phase delta connected excitation capacitor bank were considered in this analysis. It was shown in reference [4] that a resistive load of susceptance G across two phases can be converted into a balanced three-phase system by connecting a capacitive susceptance of $G/\sqrt{3}$ across the other two phases and an inductive susceptance of $G/\sqrt{3}$ across the remaining two phases in delta as shown in Fig 2.

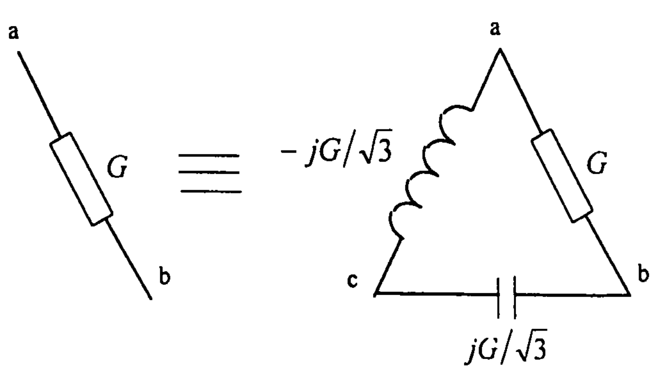

Fig 2: Load balancing by connecting an inductor and a capacitor

Now if three excitation capacitors of value $G/\sqrt{3}$ are connected across each phase in delta, where $\omega C = G/\sqrt{3}$, the following circuit can be obtained.

(a) Between a and b - a resistor and a capacitor of value C

(b) Between b and c - a capacitor of value 2C

(c) Between c and a - no passive components.

That is, the resultant external circuit becomes the same as the external components shown in Fig 1 and it satisfies the current relationships given in equations (1) and (2). Therefore, the circuit shown in Fig 1 can be resolved into the single-phase load, its associated balancing circuit and a three-phase delta connected capacitor bank. In the existing induction generator schemes, as the total load is maintained at a constant by controlling the ballast load, balancing circuit required is always the same. Therefore two fixed capacitors ensure that equations (1) and (2) are always satisfied irrespective of the operating load.

In the absence of the electronic ballast any change in the load results in changes in its associated balancing circuit thus requiring changes in the capacitors connected across each phase. First assume that the excitation capacitor bank is kept constant and the load decreases from its rated value. Thus G decreases. This results in the following:

(a) Between a and b -
- a load resistor of susceptance G' (< G)
- an excitation capacitor of susceptance $G/\sqrt{3}$

(b) Between b and c
- an excitation capacitor of susceptance
- a balancing capacitor of susceptance $G'/\sqrt{3}$

(c) Between c and a
- an excitation capacitor of susceptance $G/\sqrt{3}$
- a balancing inductor of susceptance $G'/\sqrt{3}$

This means that as the load decreases from its rated value, the total capacitance value across phases b and c is decreasing and the capacitor value across phases a and c is increasing.

In an induction generator, the generated voltage is dependant on the value of the excitation capacitance and the connected load. Therefore if the excitation capacitor is kept constant, as the load decreases the generated voltage increases. In order to maintain the terminal voltage at a constant it is required to change the value of the excitation capacitance.

3.0 Operation of the Induction Generator with a Capacitive Ballast

Fig 3 shows the features of the ballast-free induction generator based on the principles of operation outlined in the previous section. This scheme comprises two fixed capacitors C_a and C_c, a controllable inductor L and a switching capacitor bank C_b. Voltage regulation is accomplished through the controllable inductor while load balancing is achieved by the switched capacitor bank C_b.

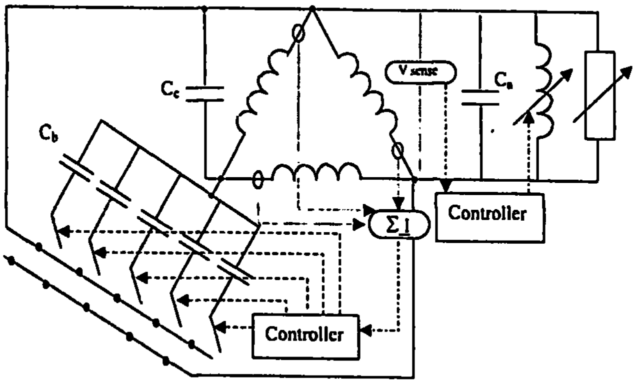

Fig 3: Ballast-free induction generator control

4.0 Analysis of the Circuit

Analysing the circuit shown in Fig 3 is not straightforward. However a proper analysis will be helpful to design the system. An iterative technique was used here for analysis. The following assumptions were made.

a) Except the magnetizing reactance all the other parameters of the equivalent circuit are constant.

b) The magnetizing characteristics are obtained at the frequency of interest for the motor and the graph may be replaced with piecewise applicable functions to model the effect of magnetic saturation.

c) Input speed was assumed to be varied with the load thus changing the working frequency for given turbine characteristics.

d) Core losses are negligible.

e) Harmonics of voltage and current waveforms may be ignored.

Fig 4 shows the equivalent circuit for the circuit shown in Fig 3. It was assumed that the capacitor values may be selected such as to obtain balanced operation thus resulting in three-phase balanced currents and generated voltages.

From Fig 4:

$$Z_1 + jZ_2 = [jX_m] // [jX_r + R_r/(F - v)] \quad (3)$$

$$Z_3 + jZ_4 = [R_L / F] // [jX_a / F^2] \quad (4)$$

$$V\angle\alpha = (Z_3 + jZ_4) \times [I\angle 0^\circ - I'\angle\beta] \quad (5)$$

$$V\angle\alpha + (R_s / F + jX_s) I\angle 0^\circ + (Z_1 + jZ_2) I\angle 0^\circ = 0 \quad (6)$$

$$V\angle(\alpha - 120^\circ) = [jX_b / F^2] \times [I\angle -120^\circ - I'\angle\beta] \quad (7)$$

$$V\angle(\alpha - 240^\circ) = [jX_c / F^2] \times [I\angle -240^\circ - I'\angle\beta] \quad (8)$$

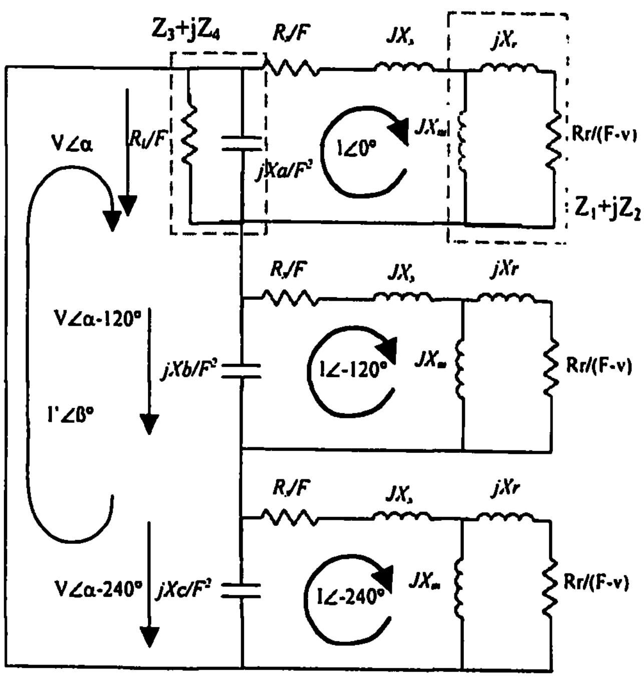

Figure 4: Equivalent circuit of the ballast-free induction generator

By equating the real part and then the imaginary part of equations (5) to (8) and using an iterative approach these equations were solved for X_a, X_b, X_c, F, I, I', α and β. The magnetizing characteristics of the machine were used to obtain a polynomial to represent the magnetizing reactance X_m.

5.0 Simulation Results and Validation

Assuming that the desired terminal voltage as 220 V and v = 1 pu, the values of X_a, F, X_b and X_c were obtained as described in section 4. The machine data together with function used to represent the magnetization characteristics of the induction machine considered for the analysis is given in Appendix 1.

Fig 5 shows the variation of the capacitors C_a, C_b and C_c required to obtain balanced operation with generated output voltage of 220 V, with different loading conditions. The experimental results obtained by driving the machine using a DC motor are also shown in the same graph with markers. Substantial agreement between the experimental and simulation results can be seen. Discrepancies are due to (a) measuring errors in capacitances and power and (b) errors introduced due to the slightly unbalanced operation of the machine.

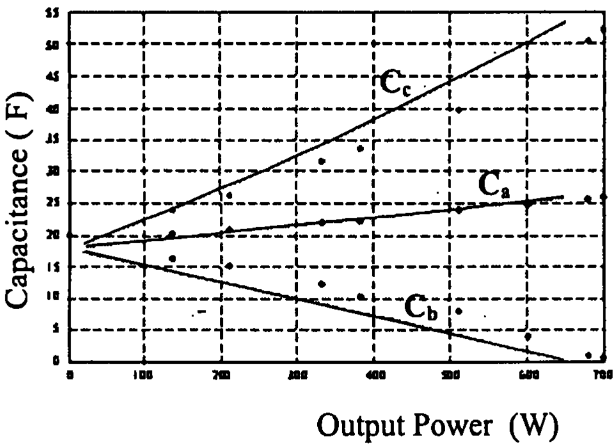

Fig 5: Variation of required capacitors to obtained desired terminal voltage and for balanced operation with load power

Fig 6 shows the frequency variation within the power variation range, when the mechanical input is kept nearly constant.

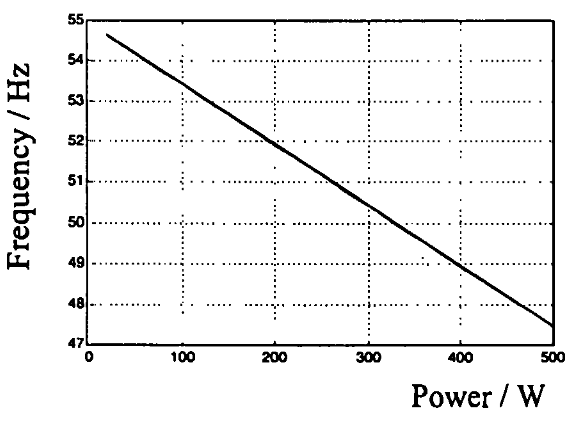

Fig 6: Variation of frequency with output power

6.0 Experimental Implementation and Results

A prototype circuit as shown in Fig 3 was implemented in the laboratory using a 1 kW induction generator. A capacitor in parallel with an open circuited transformer was used to maintain the desired terminal voltage within the full load variation range (0 - 700 W).

It can be seen from Fig 5 that the if the value of Cc is fixed at the mean value of C_b and C_c, then a switched capacitor scheme as shown in Fig 3 can be used to obtain the required capacitor values. In the system used C_c was selected as 21 μF and C_b was selected as five switched capacitors of 4 μF each. With this scheme the capacitance required for C_b and C_c was experimentally obtained by maintaining addition of three-phase currents in the motor (ΔI) less than or equal to 10mA. ΔI was measured by connecting three 120/5 current transformers in delta configuration and measuring the circulating current. Fig 7 shows the variation of C_b and C_c with output power with the switched capacitor scheme.

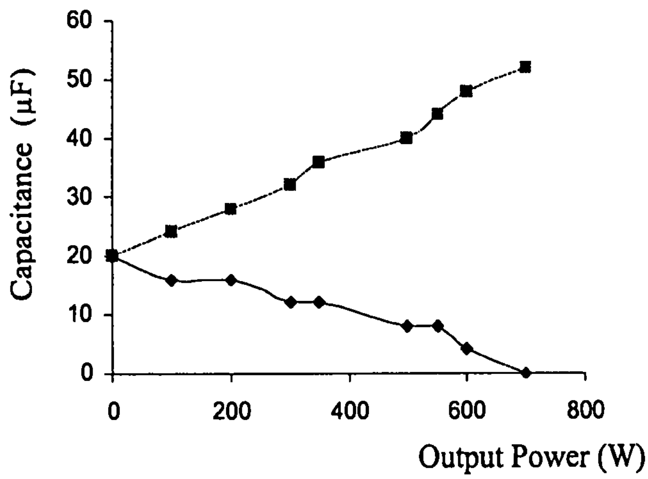

Fig 7: Variation of C_b and C_c with output power with the switched capacitor scheme

The experimental results were taken by fixing C_a at 26 μF, and smoothly controlling a parallel inductor by sensing the output voltage and changing C_b and C_c as shown in Fig 7. Table 1 summarize the results obtained.

Power (W)	ΔI (mA)	V_L (V)
0	0	220
50	10	220
100	0	220
200	10	220
300	0	220
400	10	220
500	0	220
550	10	220
600	10	220
700	0	218

Table 1: Output voltage and circulating current with scheme proposed.

7.0 Conclusions

It is common practice to use resistive ballast with induction generators. However, this has limitations especially for high power applications. A ballast based on a three delta connected variable capacitor scheme was presented. A theoretical analysis of the scheme was also presented. The scheme was validated both using computer simulations and experimental results.

A laboratory prototype of 750 W was implemented using the proposed ballast scheme. Using the experimental results, it was demonstrated that the system could be operated near balanced condition ($\Delta I \leq 10$ mA) while maintaining the output voltage at its rated value for output power variation from no load to full load.

The only limitation of this scheme is the possibility of creating inrush current whenever a switching of capacitors takes place. This can be eliminated by using a scheme having a variable inductor in parallel with fixed capacitors, very similar to the schemes used for high power Static VAR compensators.

Before using this scheme in practice, a full-scale model with a proper turbine should be constructed and tested. Further, economic appraisal is essential to compare the cost involved with respect to the cost of a small-hydro scheme based on synchronous machines and with respect to resistive ballast based induction generators.

8.0 References

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9.0 Appendix 1

Stator resistance	7.1 Ω
Stator referred rotor resistance	4.8 Ω
Stator reactance	5.3 Ω
Stator referred rotor reactance	5.3Ω

The magnetising branch was represented by the following function:

$$X_m = \frac{40 \times V_{o/c}}{V_{o/c} - 160} \ \Omega \text{ for } 210 \leq V_{o/c} \leq 230$$

where $V_{o/c}$ is the open circuit generated voltage.