Induction generators for small hydro schemes

In developing countries, small hydro projects producing power outputs in the range 1-10kW are gaining popularity, particularly as isolated power supply schemes for village electrification. These small generating plants supply power to remote locations where utility power is well out of reach. Consumer loads connected to these small hydro schemes are normally single-phase lighting loads. Therefore generators that produce single-phase output are used, partly due to the lower cost of single-phase distribution lines.

by J. B. Ekanayake

Induction generators are commonly used for small hydro schemes due to advantages such as availability, low cost and robustness. The cost per kW of a single-phase generator is generally higher than a three-phase generator. Hence a three-phase generator, which produces a single-phase output, is normally used. In order to minimise further the capital cost, crude voltage and frequency control techniques are used. The voltage and frequency are maintained within acceptable values by connecting a resistive ballast, which maintains the sum of the consumer load and the ballast load at a constant value.

A detailed description of the systems used for small hydro plants can be found in References 1, 2 and 3.
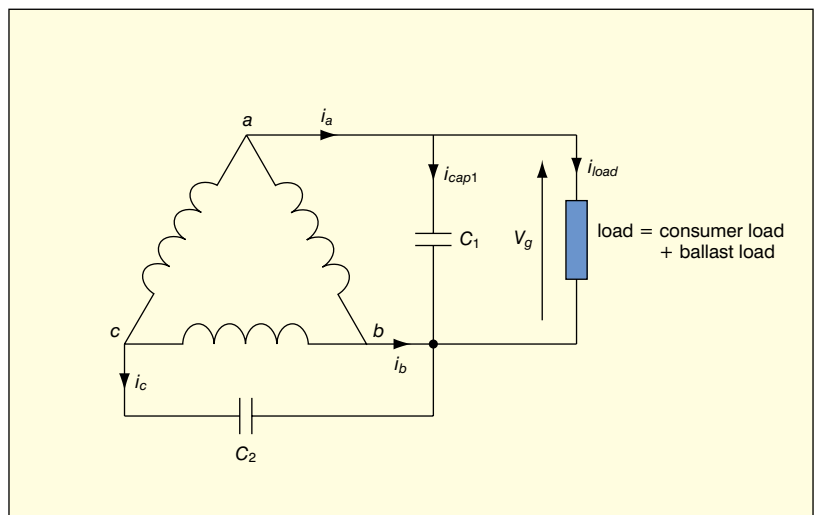
Single-phase operation of the three-phase generator

A three-phase generator can be converted into a single-phase generator, which produces approximately 80% of the machine rating, by connecting two capacitors as shown in Fig. 1. In order to analyse the circuit of Fig. 1, assume that the load connected, which is the consumer load plus the ballast load, is a constant and is resistive. This is true, as normally small hydro schemes are used to provide power for lighting and maybe for ironing clothes. From Fig. 1:
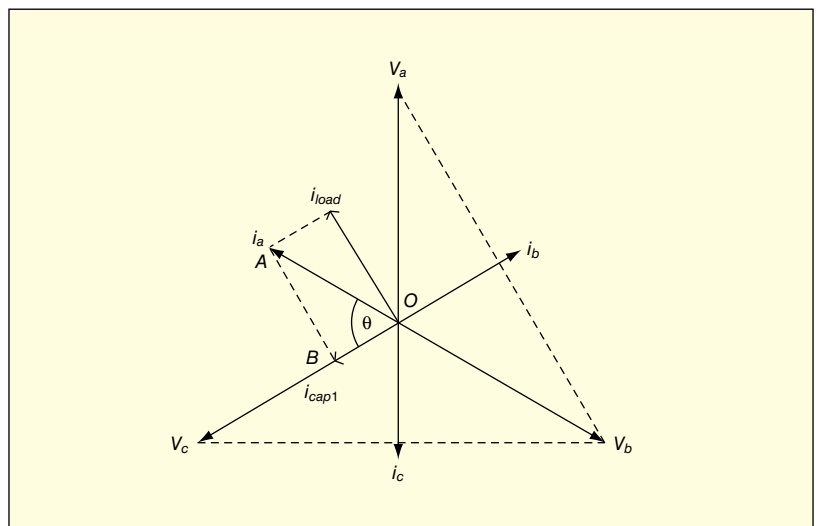
$$\bar{i}_a = \bar{i}_{load} + \bar{i}_{cap1} \qquad (1)$$

$$\bar{i}_b = -(\bar{i}_a + \bar{i}_c) \qquad (2)$$

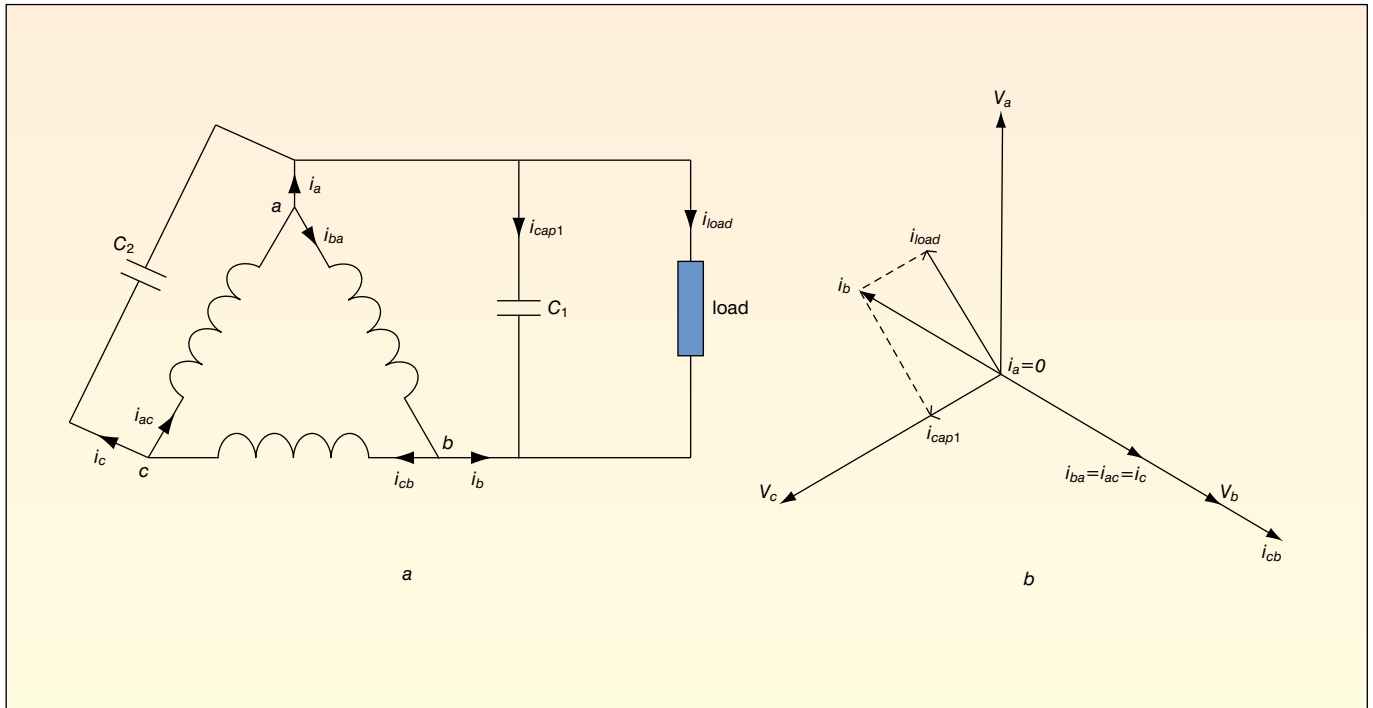Using eqns. 1 and 2 and assuming that the

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

2 Phasor diagram for the single-phase connection

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3(*a*) **Wrong connection for *C₂*; (*b*) Phasor diagram**

machine is operating as a balanced three-phase machine, the phasor diagram can be constructed as shown in Fig. 2. As capacitor C_2 is connected across phases b and c, i_c is perpendicular to the voltage vector V_{bc}. In order to obtain balanced operation the following two conditions should be satisfied:

$$\theta = 60° \text{ and } |\bar{i}_c| = |\bar{i}_a| \tag{3}$$

Once these two conditions are satisfied, i.e. $\bar{i}_a = I\angle 0°$ and $\bar{i}_c = I\angle -240°$, then from eqn. 2,

4 **Water wheel (courtesy of IDEA, Kandy, Sri Lanka)**

$\bar{i}_b = I\angle -120°$ (where I is the RMS value of the balanced three-phase currents).

The conditions for balanced operation can be expressed in terms of the currents as in eqns. 4 and 5. The derivation of these equations is given in the Appendix:

$$|\bar{i}_c| = 2|\bar{i}_{cap1}| \tag{4}$$

$$|\bar{i}_{load}| = \sqrt{3}|\bar{i}_{cap1}| \tag{5}$$

That is, in order to obtain balanced operation of the three-phase motor, capacitor C_1 should be selected such that eqn. 5 is true, and also from eqn. 4 capacitor C_2 should be equal to $2C_1$.

When an induction generator is used in this way, particular care must be taken over the connection of the capacitor C_2. If capacitor C_2 is connected between phases a and c instead of c and b as shown in Fig. 3(*a*), then the resultant phasor diagram is shown in Fig. 3(*b*). In this case, the generator will run as an unbalanced system. It can be seen that the current through one of the windings of the induction generator becomes twice that of the other winding currents. Under this condition, the generator winding will overheat. Therefore, correct connection of the capacitor C_2 is important.

Induction generator

In typical induction generator based small hydro schemes, the turbines used are run of the
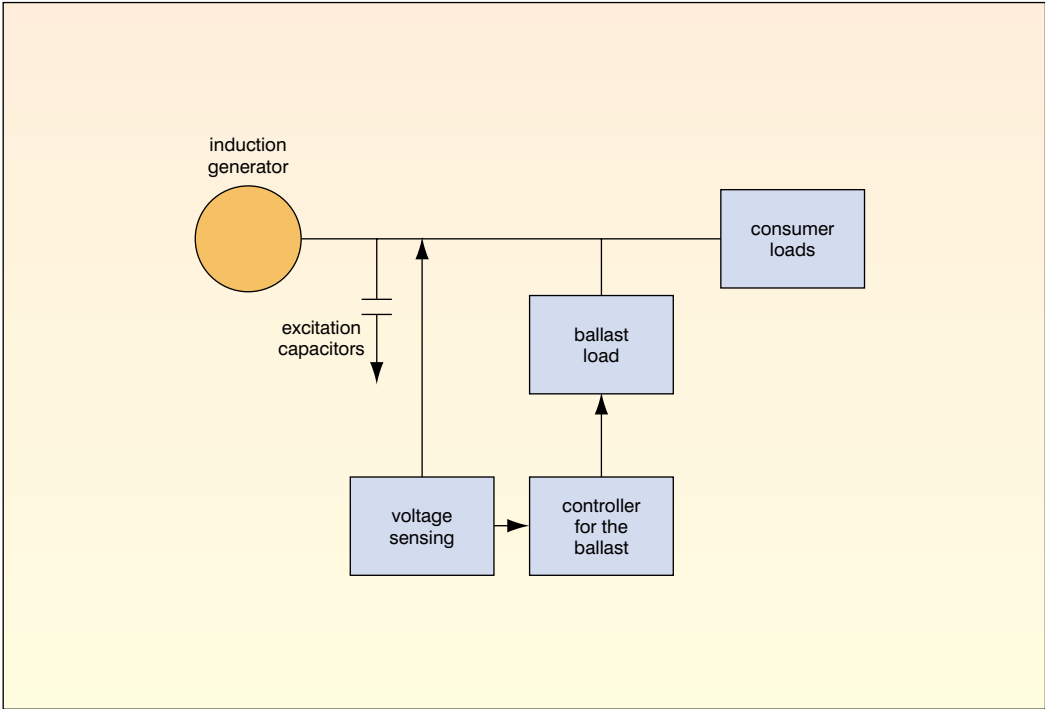
river type, where the water input and thus the mechanical power into the generator cannot be controlled. Fig. 4 shows an application of a water wheel as a turbine. In these schemes, the generator operates under manual control of the sluice gate and, if the consumer load changes, then the generated voltage and the frequency also vary. If the load is light the generator speed can increase, leading to runaway condition. The control technique used to maintain the generated voltage and the frequency at its rated value is to maintain the total load connected to the machine at near constant using a ballast load. Since the terminal voltage under this condition is a constant, voltage sensing is used to control the ballast load. The ballast load is a variable load where its resistance is controlled so as to maintain the consumer load plus the ballast load at a constant. A schematic of such a scheme is shown in Fig. 5.
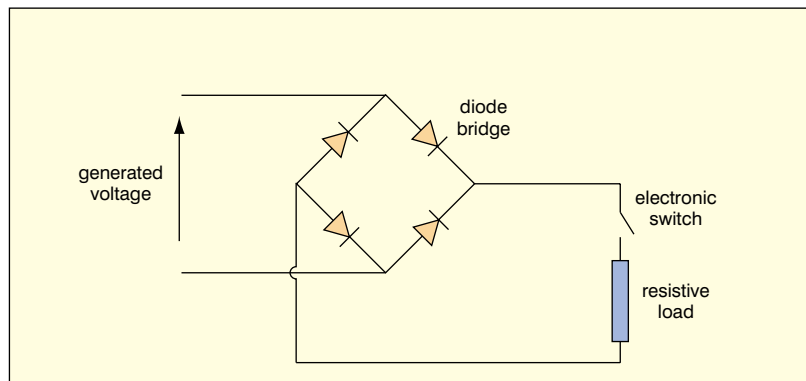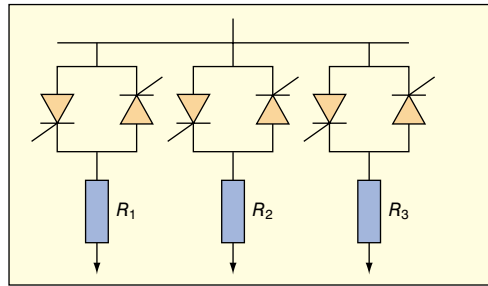
The ballast load can have many configurations. One way of obtaining a variable load is to use a resistor with two anti-parallel thyristors operating in phase control mode as shown
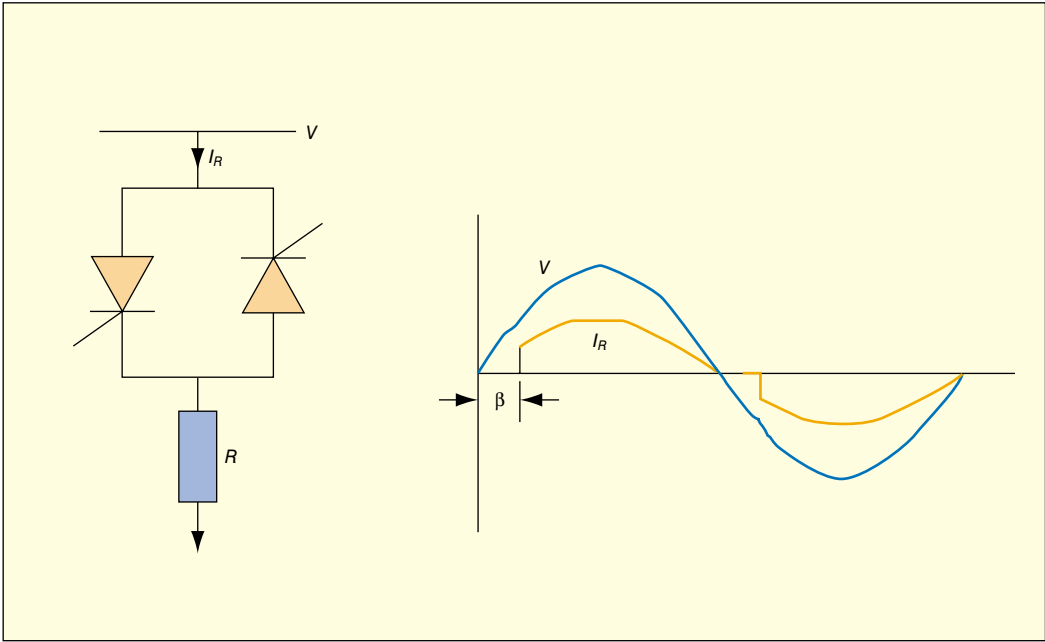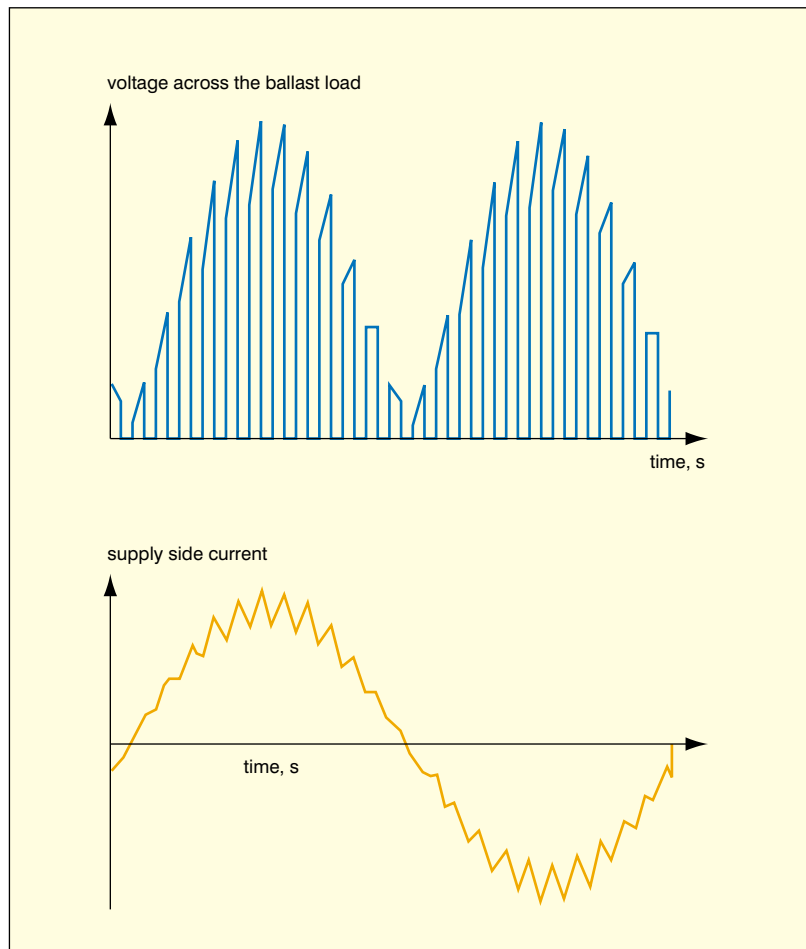

6 Thyristor phase controlled ballast load

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7 Thyristor switched ballast load

8 High–frequency ballast

9 Voltage across the ballast load and supply side current for high-frequency ballast with a 50% loading on the machine

in Fig. 6. By changing the firing angle β, the fundamental value of the current going through the resistor-thyristor circuit can be controlled. When β = 0°, full current passes through the resistor-thyristor circuit, thus giving maximum load. When β = 180°, current through the resistor-thyristor circuit is zero. For values of β in between 0° and 180°, current through the ballast load varies between its maximum and zero, thus acting as a variable resistor. However, as β is increased, the displacement factor of the resistor-thyristor circuit increases, thus absorbing reactive power. Under this condition, the resistor-thyristor circuit draws reactive current from the excitation capacitors, thus reducing the effective capacitance available to supply magnetisation current to the induction generator. This will cause a slight reduction in the generated voltage.

Another circuit, which does not absorb displacement current, uses a number of resistors with a switched thyristor scheme. The circuit is shown in Fig. 7. In this circuit, the back-to-back thyristor pair operates either as a closed or open switch. Hence the load may be varied by controlling the number of parallel resistor-thyristor circuits, which are 'on'. Therefore, the variation of the load is in steps and smooth variation is not possible. In order to get a better resolution from the circuit in Fig. 7, resistors can be selected in binary weighted form. If $R_1 = R$, $R_2 = 2R$ and $R_3 = 4R$ then the load can be varied from 0 to $7R$, in steps of R.

As indicated above, the thyristor-based circuits have some drawbacks. A circuit that exhibits smoothly varying ballast load with unity power factor operation is shown in Fig. 8. In this circuit, the electronic switch is operated at a high frequency, thus chopping the rectified AC voltage. The effective resistance of the ballast load can be changed by varying the duty ratio of the switch. Fig. 9 shows the voltage across the ballast load and the AC side current when the consumer load is only 50% of the rated load of the machine. As can be seen from Fig. 9, due to the inductance of the generator, the current drawn from the generator is nearly sinusoidal with a super-imposed high-frequency ripple component.

The electronic switch may be a transistor, a MOSFET or an IGBT. Most of the latest circuits employ IGBTs. However, when employing IGBTs, extra care must be taken against spikes generated during the switching transients as

IGBTs are easily damaged. Fig. 10 shows an IGBT based ballast circuit, normally referred to as an induction generator controller (IGC), operating in a typical small hydro scheme in Sri Lanka.

Designing components of small hydro systems

The design procedures of the IGC are well documented in References 1 and 3. The other main component, which determines the proper operation of the induction generator, is the excitation capacitor. The values of the capacitors (C_1 and $C_2 = 2C_1$) determine the power output and the terminal voltage of the generator.

In order to select a suitable excitation capacitor, rules of thumb are normally used. For a given rated induction generator, the value of the capacitor required is given in Reference 1. However, a proper design procedure to determine the value of the capacitor is clearly desirable. This section presents a design technique that can be used to determine the value of the excitation capacitor (C_1) to obtain the balanced operation of the induction generator.

From eqn. 5, in order to run the machine with single-phase loading and with minimum unbalance, the power output of the generator
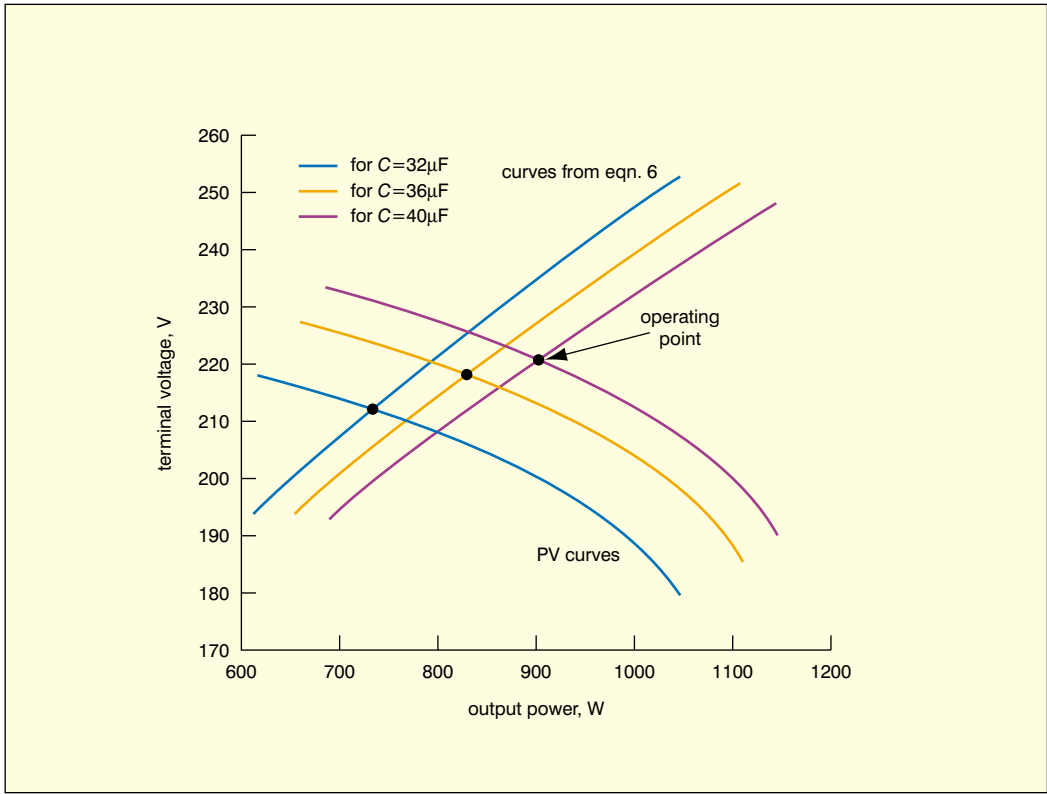
and the value of the excitation capacitor (C_1) connected across the load should have the following relationship:

$$\text{output power of the generator} =$$
$$V_g i_{load} = \sqrt{3} V_g i_{cap} = \sqrt{3} V_g^2 \omega C_1 \qquad (6)$$

Under the condition given in eqn. 6, it can be assumed that the induction generator is operating near balanced condition. Therefore, the terminal voltage characteristics of the induction generator, the PV curve can be found for different capacitor values using the conventional induction generator steady-state equivalent circuit.[4] The PV curve includes a representation of the saturated magnetising

Figure: terminal voltage, V (vertical axis, 170–260) vs output power, W (horizontal axis, 600–1200)
- for C=32µF
- for C=36µF
- for C=40µF
- curves from eqn. 6
- operating point
- PV curves

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reactance of the machine. When deriving the PV curve, the loading and operating speed of the machine are also taken into account. Intersections of the terminal voltage characteristics and that obtained using eqn. 6 give the operating points of the machine which satisfy both the steady-state machine equivalent circuit and eqn. 6.

This design method was used to design a small hydro scheme using an induction machine rated at 1·1 kW, 240 V, 50Hz. Fig. 11 shows the PV curve and the characteristics obtained using eqn. 6 for three different values of the excitation capacitor. It can be seen from Fig. 11 that, if the value of the excitation capacitor (C_1) is chosen as 40µF, then the generator produces 900W (82% of its rated output) at 220 V.

The small hydro scheme of the design example is now in operation in a site in the hill country in Sri Lanka, supplying power to ten houses in a remote village. Fig. 12 shows the on-site measurements of the three-phase currents of the induction generator. In Fig. 12,

the phase information of the three-phase currents could not be captured due to measuring limitations of the oscilloscope used on site. However, phases are well balanced and at near 50Hz frequency.

Runaway situation

Under lightly loaded conditions or under no load, if the ballast load fails then only a small part of the mechanical power input is converted into the electrical power. Since the turbine is run of the river type, the mechanical power into the turbine cannot be controlled. Therefore, the turbine and the generator will accelerate to runaway speed within a few seconds. The runaway speed depends on the turbine chosen. When runaway occurs, the torque speed characteristic is mainly governed by the turbine, and the speed increases to that corresponding to the torque, which is just enough to overcome the friction and windage loss of the system. For the commonly used cross-flow turbine, runaway speed is around 175% of the optimum speed. Under runaway
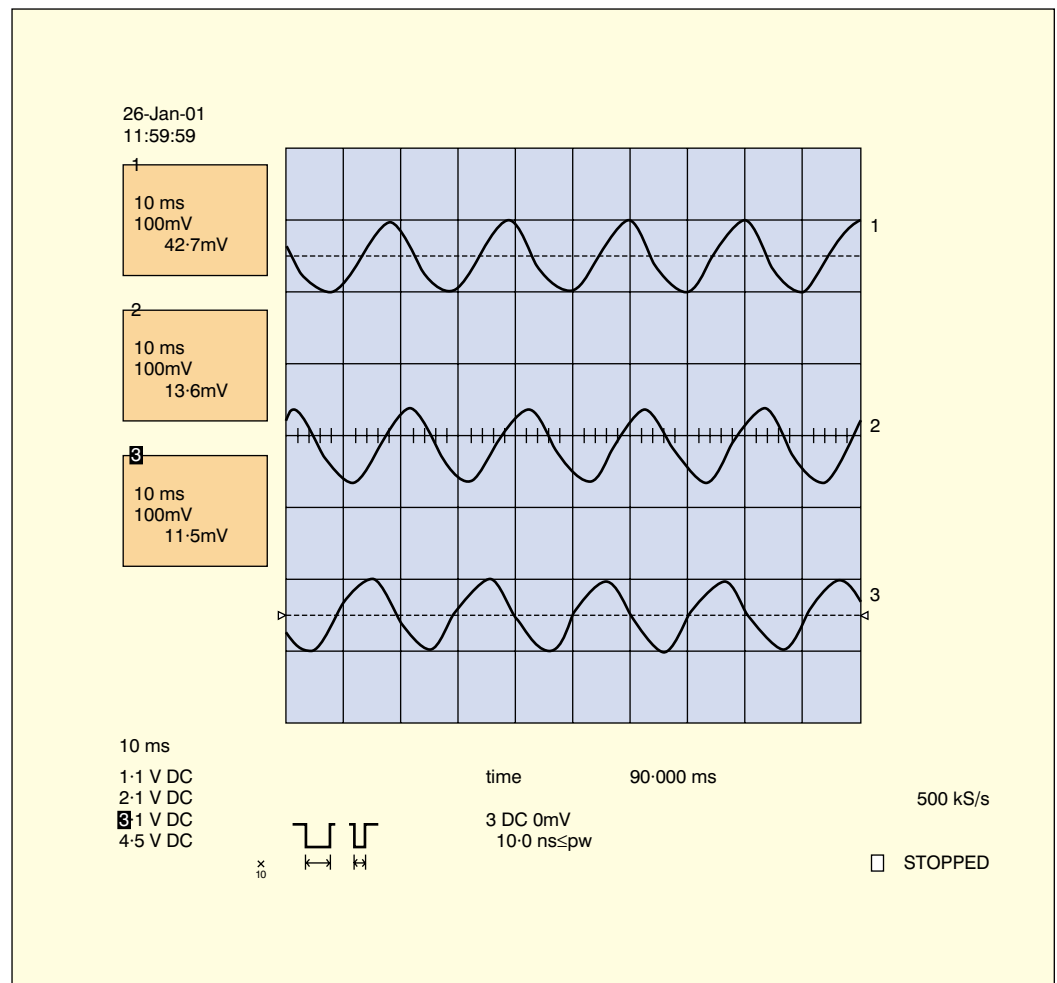
12 Three-phase currents of the induction generator
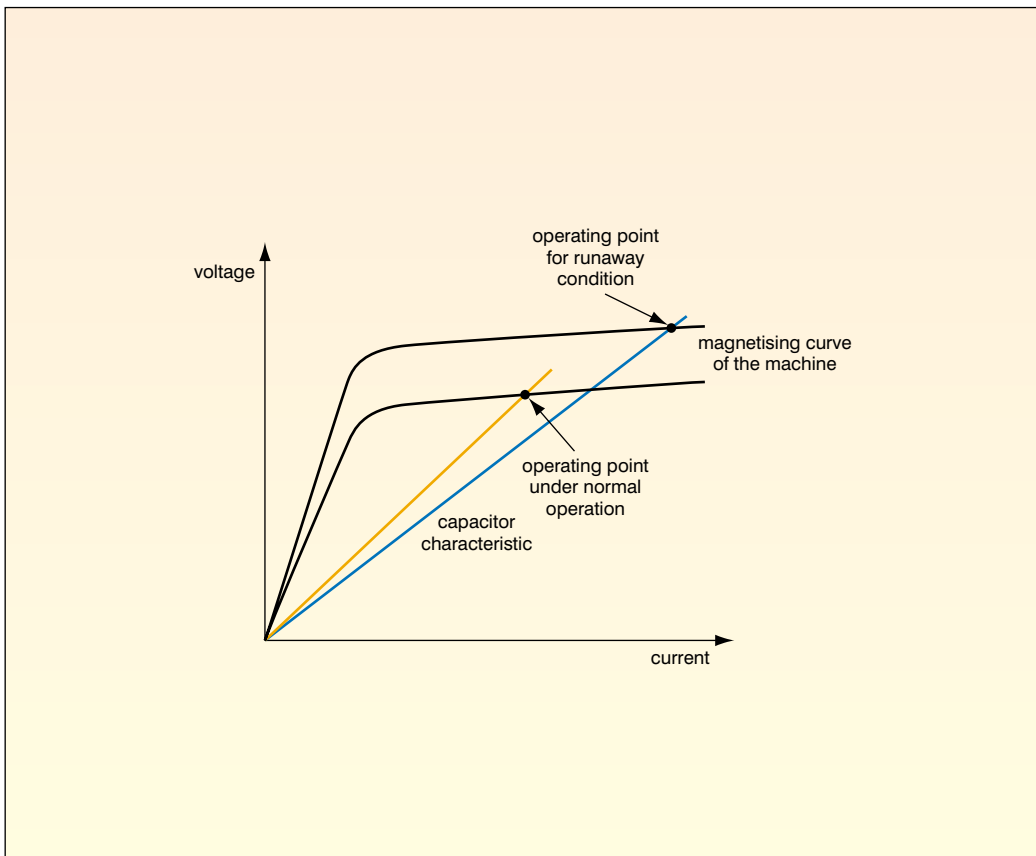
condition the generator voltage will also increase as shown in Fig. 13. This can cause extensive damage to the generator, connected loads and excitation capacitors.

In order to prevent damage to the generator and the connected loads during the runaway condition, the IGC is normally equipped with an overvoltage protection circuit. When the generated voltage raises above a certain set limit, the overvoltage protection isolates the excitation capacitors and the loads from the generator, thus allowing the induction machine to run without any generated voltage.

Conclusions

The principle of operation of the three-phase induction generator under single-phase loading has been presented. In order to obtain the balanced operation of the induction generator, proper selection and connection of two capacitors C_1 and C_2 is essential.

Design criteria have been shown to determine the value of the excitation capacitors and the loading on the generator. A system implemented in Sri Lanka using this design criteria has demonstrated the balanced operation of the generator and is presently giving satisfactory service.

Appendix

From the triangle OAB of Fig 2, using the conditions given in eqn. 3, the following can be seen:

$$\tan\theta = \frac{|\bar{i}_{load}|}{|\bar{i}_{cap1}|} = \sqrt{3} \qquad (7)$$

$$\cos\theta = \frac{|\bar{i}_{cap1}|}{|\bar{i}_a|} = \frac{|\bar{i}_{cap1}|}{|\bar{i}_c|} = \frac{1}{2} \qquad (8)$$

References
1 SMITH, N. P. A.: 'Motors as generators for micro-hydro power', Intermediate Technology Development Group publication, 1994
2 SMITH, N. P. A.: 'Induction generator for stand-alone micro-hydro systems, Proceedings of the International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, 1996, 2, pp. 669-673
3 http://www.microhydropower.net/download/manuals.html
4 WAGNER, C. F.: 'Self-excitation of induction motors', *AIEE Transactions*, 1939, **58**, pp. 47-51

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