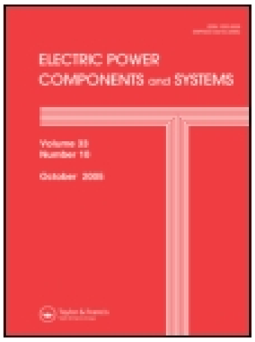

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Wave energy can meet a sizeable portion of the world's energy needs. For countries having long coastlines, wave energy conversion is an attractive proposition. Wells turbine driven grid-connected systems with squirrel cage induction generators have been in existence; however, rotor-side control of grid-connected induction machine is an attractive option for variable speed constant frequency operation. The power rating of the converter can be considerably reduced when used in the rotor circuit over a limited slip range (approximately 50%). Since the stator is directly connected to the grid, the stator flux is constant over the entire operating region. Therefore, the torque can be maintained at its rated value even above synchronous speed. This article describes the simulation of a rotor side chopper controller for wave energy.

Keywords induction generator, wave energy, wells turbine

1. Introduction

Wave energy is oscillatory. Although the Wells turbine [1–5] rectifies the airflow, the turbine torque still varies periodically from a positive peak to zero and again to a positive peak every 4 to 5 seconds. The power fed to the grid has a large peak to average ratio (typically 15) [6]. Fluctuations in speed are reflected as fluctuations in power owing to the tight coupling between the squirrel cage induction generator and the grid. The size of the electrical generator has to be large to cope with such high peak powers. Thus, the machine operates most of the time at low load, resulting in low efficiency. The electrical machine has to operate in both motoring and generating modes very frequently. The Wells turbine consumes power at low values of air velocity. These factors reduce the average power generated, and such a performance is undesirable. Hence, a well designed and properly controlled electrical drive is required to generate a controlled steady electrical power.

The rotor side controller fulfills the following objectives—-reduces the ratio of peak power to average power to a value close to unity, provides motoring torque to help start

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non-self starting turbines, provides smooth transition between motoring and generating modes and generates power at a high power factor and low harmonic content.

2. Simulation of Un-Controlled Generator

The SIMULINK diagram for the Wells turbine is shown in Figure 1. Here the curve of turbine torque coefficient C_T versus angle of incidence of air α has been borrowed from [2]. Turbine torque is a function of shaft speed ω_m and axial air velocity v_x. A sinusoidal steady-state model has been used for the induction generator since speed variations are sufficiently slow compared to electrical time constants, as shown in [6]. Figure 2 shows the model of the overall system. The feedback loop computes the required rotor resistance from the slip and supplies it to the machine model at each instant. The ripple produced in the current by the chopping action is ignored here since chopping at a sufficiently high frequency can reduce it. Axial air velocity vs. time data collected from a wave energy site was used as the input data. Table 1 shows the simulation result for the uncontrolled machine for two fixed values of rotor resistance.

From Table 1 we conclude that the uncontrolled system value of fixed rotor resistance does not have an appreciable effect on peak to average power ratio, which is unacceptably large. Hence, for wave power schemes using Wells turbine, a grid connected, squirrel cage induction generator scheme is not suitable.

It is proposed to design the controller so as to clip the power peaks at a value close to the average power. This will result in smaller power peaks. At the same time, the excess power over the clipped level, which is undelivered to the grid, will accelerate the system and result in stored kinetic energy in the inertia of the system, which will be used in the lean period of the wave cycle when less power is available. Some form of feedback will need to be used. This will result in smoother power flow. The increased speed variation will favor the turbine with better incidence angles so that the power captured by the turbine will increase.

Among plausible controllers, the stator voltage controller has a small control range and high harmonic content. The voltage source inverter fed induction machine drive [7] and cycloconverter drive [8] were ruled out owing to their complexity and number of components. The current source inverter fed induction machine drive was analyzed on

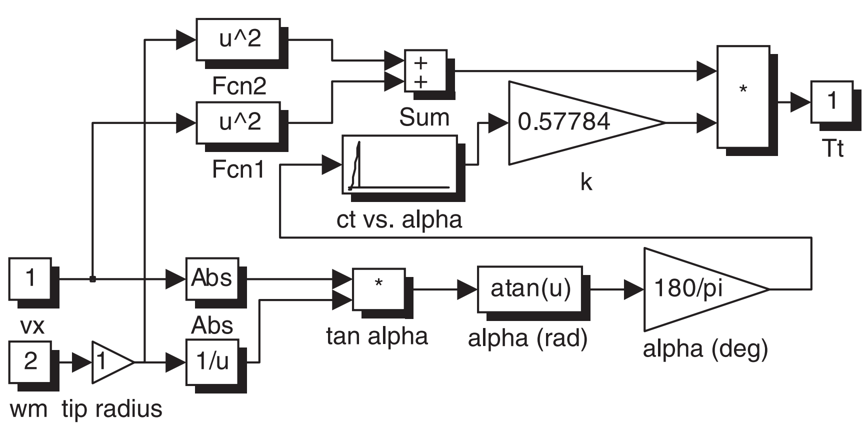

Figure 1. Simulink model of the Wells turbine.

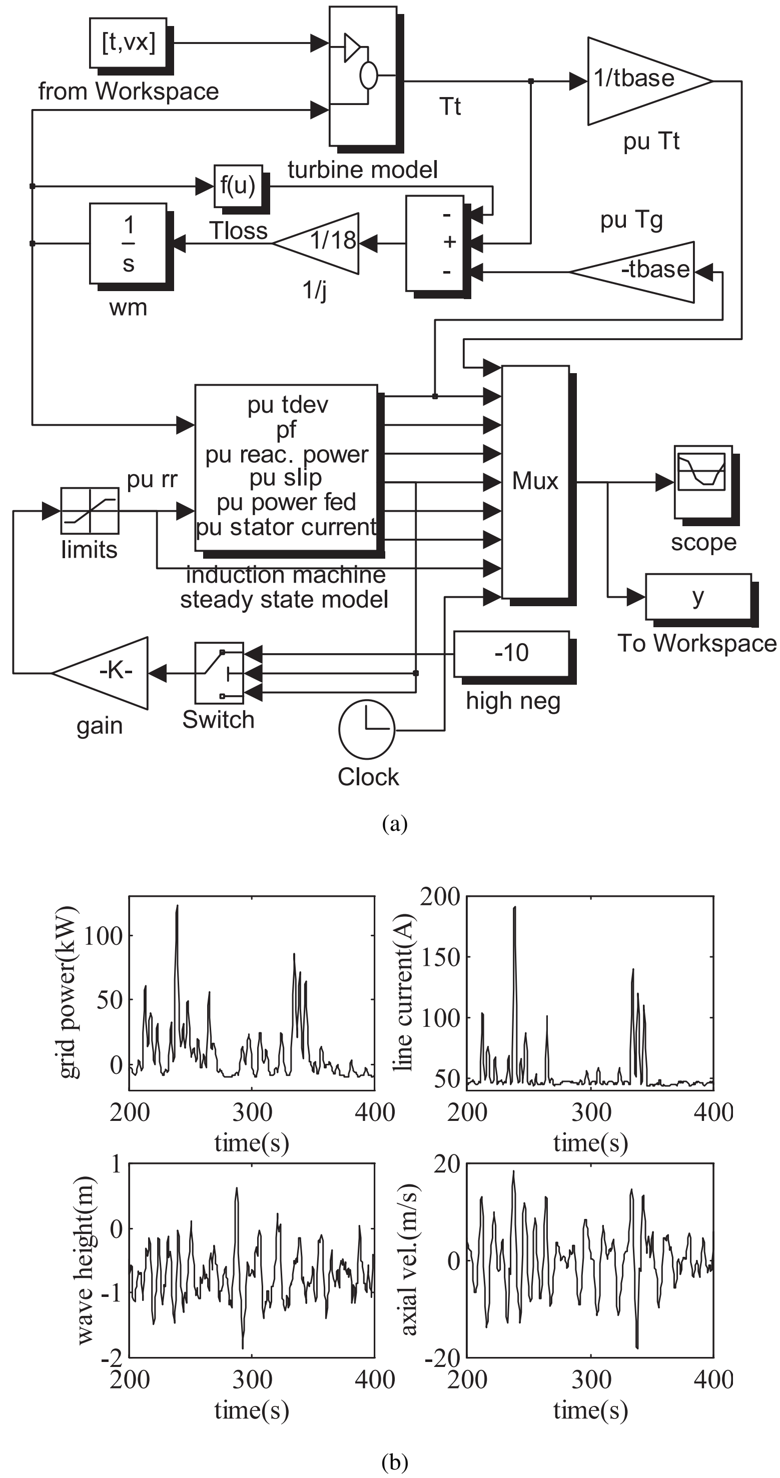

Figure 2. (a) SIMULINK model of a wave energy system with a rotor resistance chopper, and (b) Simulation result for the uncontrolled generator for rotor resistance 0.0334 Ω.

Table 1
Simulation results for uncontrolled generator with two different values of fixed rotor resistance

Rotor resistance	Mean power (kW)	Peak power (kW)	Peak/ mean power	Mean stator amps	Peak stator amps	Peak rad/s	Mean p.f.
$R1 = 0.0334$ ohm	22	213	9.68	60	313	107	0.42
$R2 = 0.3751$ ohm	22	234	10.6	59	351	159	0.41

the stator and rotor sides, but did not prove satisfactory, and was given up [9]. Hence, an attempt is being made to study control from the rotor side.

3. Simulation of Generator with Rotor Resistance Controller

In rotor side control, varying the effective value of rotor resistance can vary the slope of the torque-slip curve dynamically with slip changes. This would require the generator to be of the slip ring variety. The rotor voltage is rectified and applied to a power electronic chopper connected across a large fixed resistor [10–12]. The chopper is used to vary the effective value of the external rotor resistance in a controlled manner so that the power is clipped. This implies that the effective rotor resistance must be varied in proportion to the slip.

However, when the rotor resistance is varied in proportion to the slip while keeping the stator voltage constant, the equivalent circuit becomes frozen, i.e., rotor current, stator current, power and torque all become constant. Hence, rotor current can be used as the feedback quantity instead of power or slip. In other words, slip does not have to be measured. The rectified rotor current is taken as the feedback quantity and is compared with a fixed reference value. The configuration of the controller is shown in Figure 3.

If $R2$ is the value of the fixed external resistor and Δ is the duty cycle of the chopper, defined as the ratio of off time to time period, then the effective resistance as seen in the chopper would be $\Delta^* R2$. Thus, the effective value can be changed from 0 to R in very small increments. The stator of such a machine can be directly connected to the mains so that the stator voltage is undistorted. Also, no harmonic currents are reflected to the stator side since a diode rectifier is used on the rotor side. During motoring (positive slips),

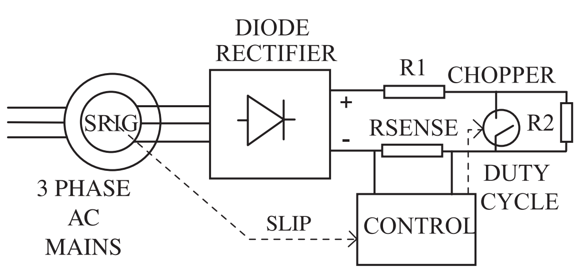

Figure 3. Slip ring induction generator with rotor resistance controller.

the power drawn from the grid can be minimized by keeping the off-time of the chopper large so that a large effective rotor resistance is included. This will allow the system to accelerate and store kinetic energy in the inertia.

The inclusion of a resistor in the rotor circuit entails slip energy losses, making the system less efficient. However, the power factor improves substantially. Slip energy recovery can be used to recover this energy by replacing the passive resistor with active components such as batteries to absorb the power. Auxiliaries in the control room, such as emergency brakes, lighting, fans, personal computer supplies and air conditioners, can use the power dumped into the batteries. At larger power levels, one can utilize it for other useful applications such as desalination, hydrogen generation, battery charging, electrolysis, etc.

The principle of operation of this controller is explained with reference to Figure 4, which corresponds to a set power value of 45 kW. When the wave power is low, the induction machine operates as a motor at A. In the motoring zone from A to B, the effective rotor resistance is made high so that the machine draws less power from the grid. When wave power increases, the system accelerates to synchronous speed at B, where the controller reduces the effective rotor resistance to the internal resistance value. The machine then accelerates to point C along the normal characteristic curve corresponding to the internal resistance value. At C, the generated power reaches the set value and clipping comes into action. During the clipping, the effective rotor resistance is changed continuously in proportion to the slip, so that power remains at the set value in spite of the change in slip. The zone C to F indicates this. The result of simulation is summarized in Table 2 for 25 kW clipping.

4. Simulation of Generator with Rotor Resistance Controller and Reduced Stator Voltage

A transformer tap changer on the stator side and a resistance chopper on the rotor side can also be used for the control, as shown in Figure 5. Here the main control action is from the rotor resistance controller. The rotor chopper permits us to have constant torque or constant power mode of operation for the drive while the tap changer permits us to have better power factor and efficiency under light load conditions [13]. A reference is set for clipping the power fed to grid as a function of slip as in the rotor resistance controller cases studied earlier.

5. Finding the Optimum Stator Voltage

During lean period of waves, the generator is lightly loaded. During such periods it is advantageous to apply reduced stator voltage, which results in better power factor and efficiency [13]. For a given power clipping level it is found that there is an optimum value of stator voltage, which gives maximum power factor and nearly maximum efficiency irrespective of the speed of operation. This value corresponds to the point marked by an ‘x’ on the power factor curve in Figure 6.

The operation of this controller is illustrated in Figure 7 for a set power value of 45 kW. This figure can be compared with Figure 4. Here, in addition to the rotor resistance controller, the stator voltage controller has also been incorporated in order to apply the optimum voltage. Hence, the induction machine operates from C to F at the maximum

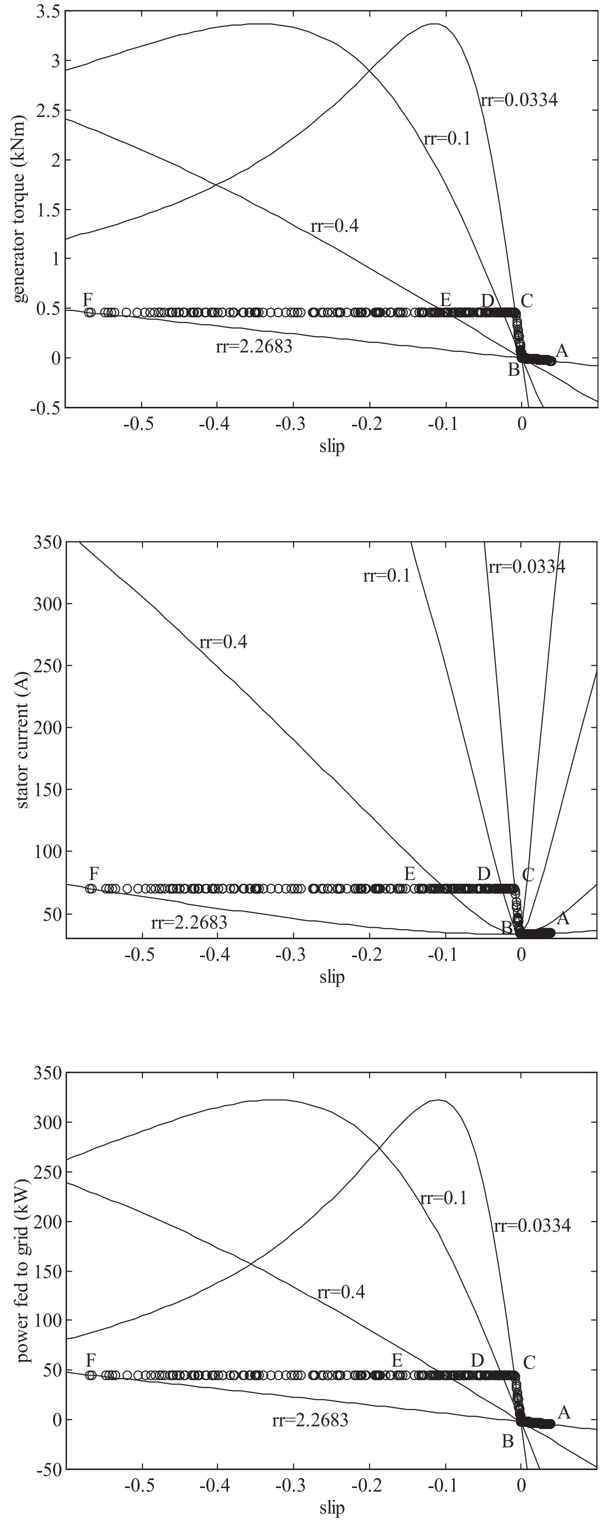

Figure 4. Operation of rotor resistance controller with a power setting of 45 kW.

Table 2
Simulation results of rotor resistance chopper with 25 kW power clipping

Mean power (kW)	Peak power (kW)	Peak/mean power	Mean stator amps	Peak stator amps	Peak rad/s	Mean p.f.
12	25	2.0	42	48	347	0.45

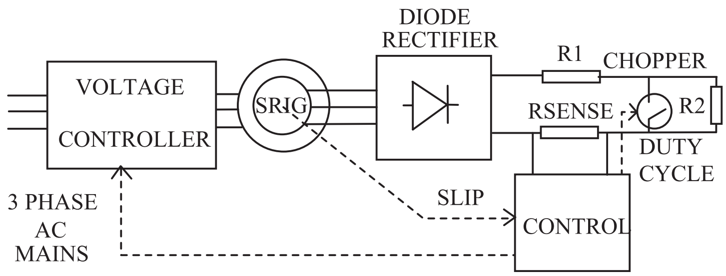

Figure 5. Slip ring induction generator with rotor resistance controller and reduced stator voltage.

power factor corresponding to the set power value. The result of the simulation is given in Table 3.

6. Discussions and Conclusion

From Tables 1, 2, and 3 we can draw the following conclusions: As compared to the use of a squirrel cage induction generator configuration, use of a slip ring induction generator configuration with rotor resistance chopper for wave energy operated OWC Wells turbine driven grid-connected schemes results in improvement of both the energy conversion efficiency as well as dynamic performance. The method gives lower power fluctuation and higher power factor than the uncontrolled cases.

When the optimum reduced voltage is applied to the stator along with the chopper in the rotor side, further improvement in performance results. The power factor improves further at the cost of increased current. All other quantities remain practically unchanged. The clipping level can be chosen at about 1.2 times the average value of power available in the uncontrolled system.

In order to reduce line current harmonics, one can have a transformer tap changer on the stator side in place of a phase-controlled controller. One could even do away with the tap-changing transformer and have the machine designed for a higher voltage, i.e., with unsaturated magnetic structure, which gives similar benefits as with a stator voltage controller. But in this case the applied voltage will have to be fixed at a non-optimum value. Thus, a properly designed slip ring induction generator with rotor resistance chopper and constant current control seems to give the best results.

The proposed controller can be used to start non-self starting turbines. It seems to have a good control range, and there is no tendency for the current to become very high since limiting the power automatically limits the current. Operation should be stable.

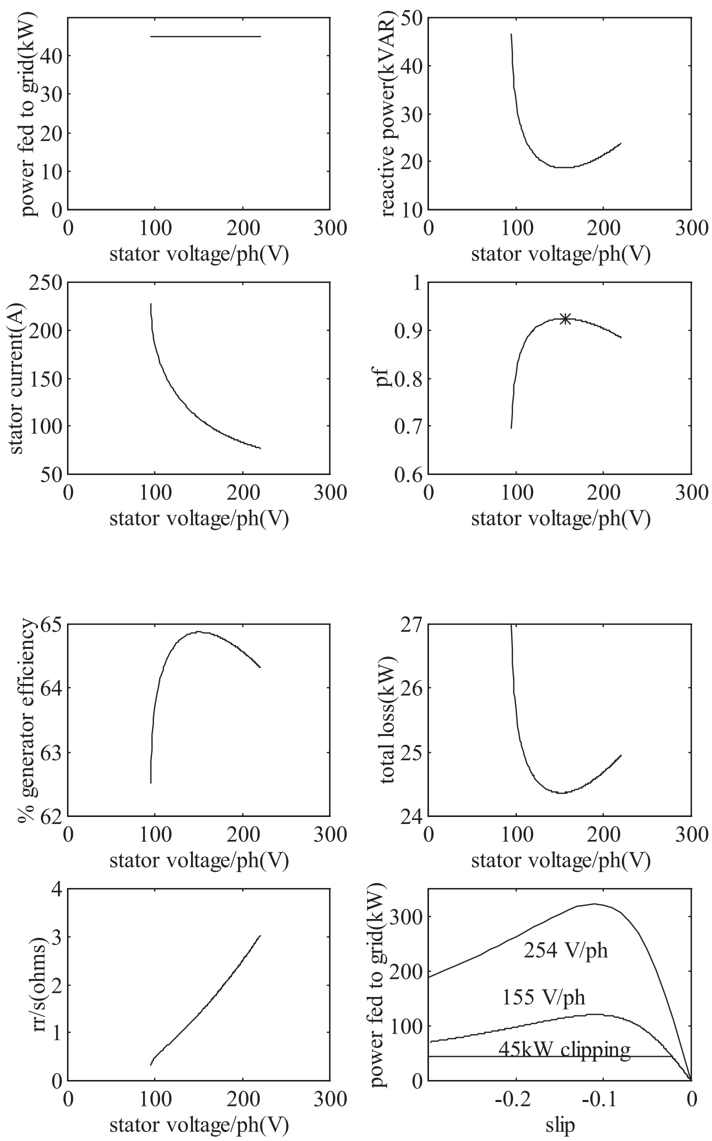

Figure 6. Finding the optimum stator voltage for 45 kW clipping level.

Table 3
Simulation results of rotor resistance chopper with reduced voltage and 25 kW power clipping

Mean power (kW)	Peak power (kW)	Peak/mean power	Mean stator amps	Peak stator amps	Peak rad/s	Mean p.f.
13	25	1.9	51	78	349	0.68

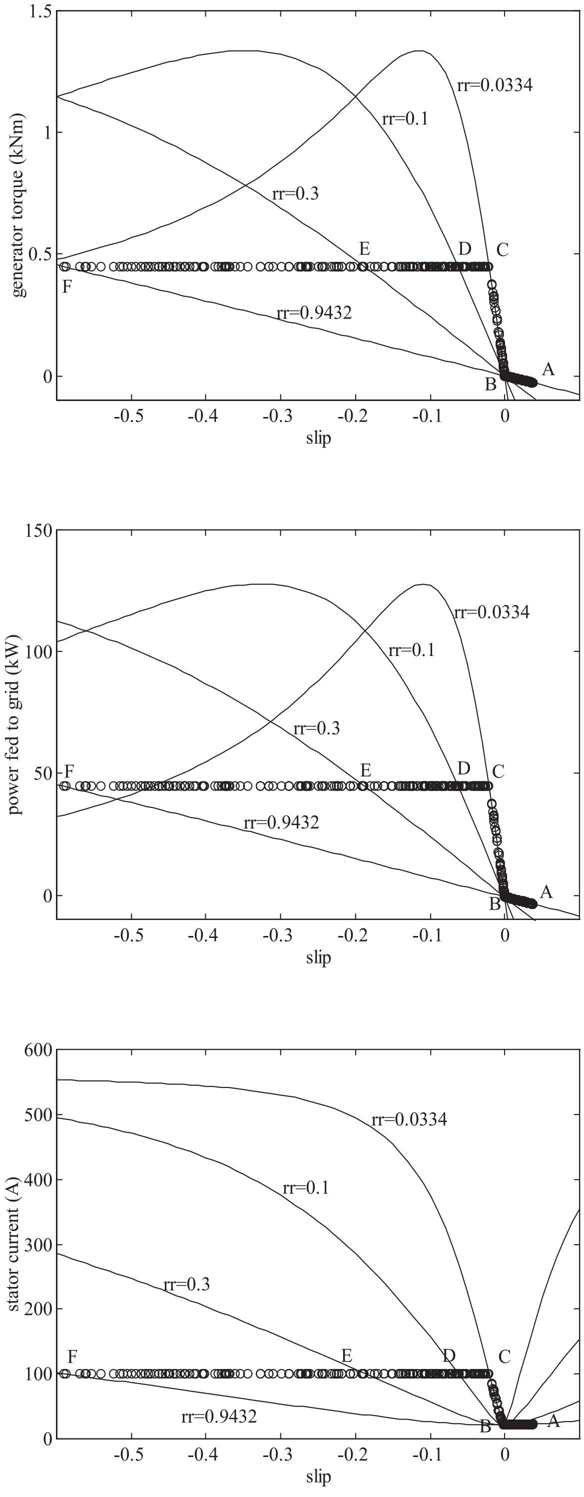

Figure 7. Operation of rotor resistance controller with power setting of 45 kW and optimum stator voltage of 160 V.

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Appendix

Generator details: 440 V, 50 Hz, 55 kW, 4 pole, slip-ring induction machine with the following parameters: $RS = 0.0181\ \Omega$, $LS = 0.4138$ mH, $RR = 0.0334\ \Omega$, $LR = 0.5093$ mH, $RM = 107.303\ \Omega$, $LM = 23.6027$ mH, $J = 18$ kgm^2, with provision to add flywheel.