A Single Phase Self-Excited Induction Generator with Voltage and Frequency Regulation for use in a Remote Area Power Supply

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ABSTRACT

Micro-hydro generator schemes are an attractive choice for electricity generation in remote locations or underdeveloped communities where a grid supply is not available. Since such systems must be low cost, reliable, and robust to minimise maintenance requirements, the use of a standard squirrel cage induction motor is appealing – either three phase or single phase depending on power ratings and availability. The principles of generation using induction motors are well established, and self generation is readily achieved by connecting excitation capacitors in parallel with the motor, to form a resonant LC circuit. However, control of the output voltage and frequency is not possible if fixed excitation capacitors are used. This paper presents a method of controlling a self-exciting single phase induction motor, where the shunt capacitance connected across the machine is varied to regulate the output voltage magnitude, while the output frequency is regulated by using a triac to vary the power fed to a resistive dump load. The paper reviews self excitation principles for a single phase induction motor, develops the voltage and frequency regulation concepts, presents the design of the microprocessor based regulation system, and then concludes with experimental results that verify the system's operation.

1. INTRODUCTION

Micro-hydro generation systems are an attractive alternative for the generation of electrical energy in remote locations where an electrical grid is not available. Typically, they are used in run-of-the-river locations, or small-dam low-head applications, and they have the particular benefit of continuous energy availability day or night, unlike energy generated from either solar or wind sources. However, it is important that such systems are robust and require minimal maintenance, since they are usually installed remote from any maintenance facilities, and are likely to be managed by un-skilled operators. Also, it is appealing to use a standard squirrel cage induction motor as the electrical generator, since these motors are the most robust and low cost type of electrical machines on the market.

The principles of generation using an induction motor are well established, and essentially require magnetising current to excite the machine, and forced rotation by a prime mover at a speed above synchronous frequency to operate the motor in the regeneration region. For grid-connected systems, such as a grid-connected wind turbine, the magnetising reactive power is supplied by the grid, and regeneration operation is automatic once the motor shaft is driven to rotate above synchronous speed. For stand-alone operation, the induction generator must be self-excited, since there is no external reactive power source. This is typically achieved by connecting capacitors in parallel with the motor magnetising impedance, to make a resonant LC circuit. However, the motor's output voltage and frequency becomes less defined under these conditions since they interactively depend on a combination of the system mechanical speed, the amount of paralleled capacitance and the connected load [1]. Consequently, many stand-alone micro-hydro generation systems simply feed their energy into a resistive thermal dump load, rather than attempting the more challenging task of regulating the motor's electrical output.

Starting up the generation system can also be quite uncertain, since the initial excitation derives from residual magnetism in the rotor, and this can be quite ill-defined. In addition, most of the stand-alone systems reported in the literature have been based on three-phase motors, which are easier to analyse. Hence there is less information available as to the anticipated performance of a self excited single phase induction motor in such systems, even though the power levels typically involved are much better suited to a single phase motor.

This paper presents a method of self-exciting a single-phase induction motor for use in low power (up to 500W) microhydro systems, so that both the output voltage and the output frequency are regulated as the mechanical input power and the system's electrical loading vary. Voltage is controlled by switching parallel excitation capacitors into and out of circuit as required to maintain a nominal $220V_{rms}$ output. Frequency is controlled by varying the power supplied to a resistive dump load, to maintain an overall load on the system that keeps the self-excitation frequency close to a nominal 50 Hz. Both control loops are integrated into a single low cost microprocessor controller, which also allows interactions between the two control processes to be damped out. The paper presents results of the machine self-excitation investigations, the design of the controller, and experimental results for a standard induction motor operating under a variety of input power and output load conditions.

2. Single Phase Induction Motor Self Excitation

2.1. Principle of Self Excitation

The principle of self-excitation of an induction motor is well known [2][3][4]. Essentially, self excitation is achieved by connecting capacitors in parallel with the motor as it is being driven by a prime-mover above synchronous speed. The resulting LC circuit made up of the external capacitors and the motor magnetising inductance forms a resonant circuit, which stabilises as the magnetising inductance saturates to oscillate at a particular frequency and magnitude depending on the motor speed and loading conditions. For any particular value of connected capacitance, there is a corresponding minimum speed at which self-excitation will occur, and self-excited induction generation systems also have inherent short-circuit protection whereby the voltage collapses to zero in the event of short-circuit on the generator output.

Recent work [4] has shown that reliable initiation of self-excitation requires a transient phenomena, because the magnetising inductance initially increases with terminal voltage, reaches a maximum, and then reduces again as the motor output rises to near rated voltage and the magnetising inductance begins to saturate. If the motor is operated as a generator in the lower voltage increasing inductance region, any slight decrease in speed will cause a reduction in magnetising inductance and lead to voltage collapse. Reference [4] recommends that this region can be avoided by switching the self excitation capacitors into the circuit once the induction motor is rotating at an adequate speed. This causes a sufficient initial transient to guarantee proper self-excitation startup.

Most of the published work regarding self excitation of an induction motor relates to a three phase motor, using the equivalent steady state circuit model shown in Figure 1(a). Figure 1(b) shows the equivalent steady state circuit model for a single phase induction motor, where the single phase winding is represented as the series connection of a forward and a backward rotating set of three phase windings [5]. It is clear from Figure 1(b) that self excitation of a single phase motor will occur in much the same way as for a three phase motor, since the magnetising inductance is still available to resonate with the external capacitance, and hence the work described in this paper proceeds from this point.

2.2. Measurement of Generator Magnetising Inductance

While the generator inductance cannot be easily measured directly, it can be approximately found by measuring the input voltage and current under zero-slip conditions, where the rotor resistance term increases to virtually an open circuit. This test was conducted on the motor used in this project by driving the motor shaft at exactly 1500 rpm using the DC load machine, and energising the stator winding with rated voltage. From this test, the single phase induction motor primary winding was found to have a self- inductance of 116mH.

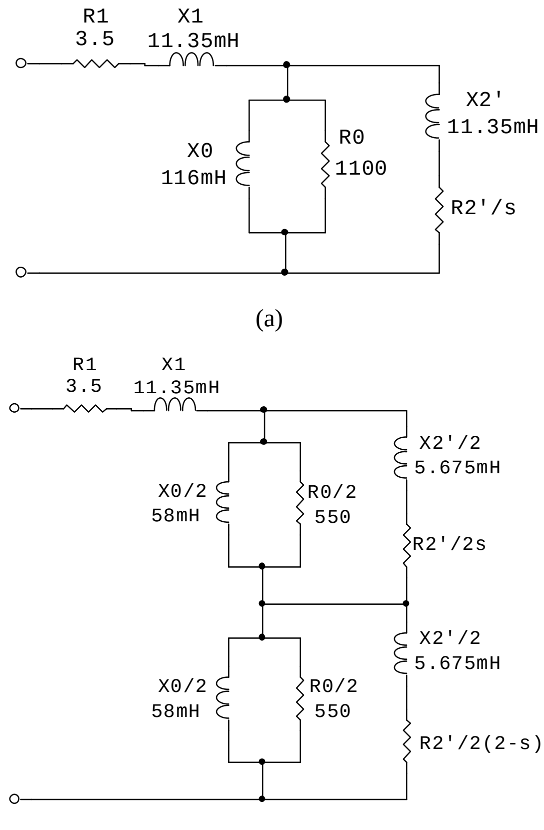

Figure 1: Steady State Model of (a) Three Phase Induction Motor and (b) Single Phase Induction Motor.

It is well known that an underdamped LC circuit will resonant at a frequency given by

$$w_o = 1/\sqrt{LC} \quad (1)$$

Hence anticipated capacitance required to achieve oscillation at 50 Hz can be calculated as:

$$C = 1/w_o^2 L = 1/\{(2p\,50)^2 116.10^{-3}\} = 87\ \mu\text{F} \quad (2)$$

Figure 2 shows the build-up of voltage achieved when 89µF of capacitance was switched across the motor stator winding while it was turning at 1500 rpm. The output frequency was measured to be just under 50 Hz under these conditions, almost exactly as expected.

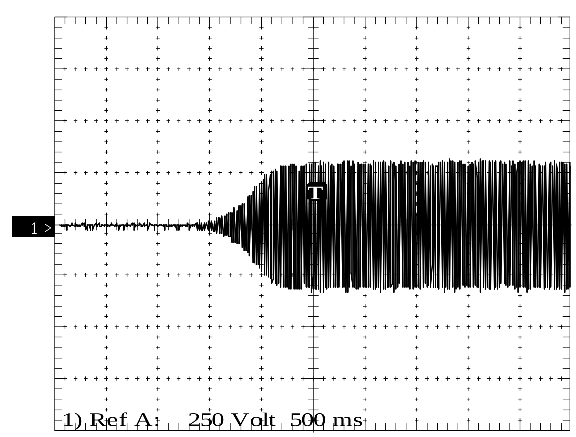

Figure 2: Self Excitation of Single Phase Induction Motor.

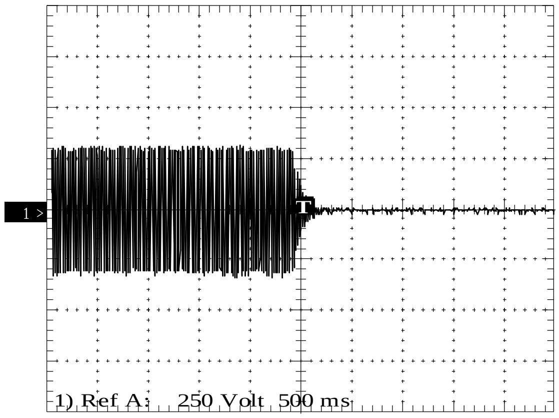

Figure 3: De-Excitation of Single Phase Induction Motor.

If the external capacitors are reduced (or disconnected), the resonant circuit no longer exists, and the AC output voltage from the motor collapses. This is shown in Figure 3 where the collapse of the self excitation voltage after the external capacitors are disconnected can be seen. The voltage decay takes about 10 cycles to reach zero output voltage.

2.3. VARIATION OF GENERATOR MAGNETISING INDUCTANCE WITH VOLTAGE

Tests were then conducted to explore the variation of magnetising inductance with voltage, while the stator winding is resonating at a constant frequency. For this test, the motor was independently driven at 1500 rpm, a variable 50 Hz voltage was applied to the stator from a variac, and the magnetising current was measured to determine the magnetising inductance. Figure 4 shows the result, where it can be seen how the inductance first increases as the voltage increases, and then reduces again as the machine begins to saturate. This result is the same as reported in [4], and identifies an unstable region of operation between points A and B that should be avoided to prevent voltage collapse.

3. VOLTAGE AND FREQUENCY REGULATION OF A SELF EXCITED INDUCTION MOTOR

3.1. VOLTAGE REGULATION

The principle of voltage regulation proposed in this paper is to switch capacitance in or out of the circuit to maintain a constant output voltage as the load and speed conditions vary. Essentially, the self-excited voltage at

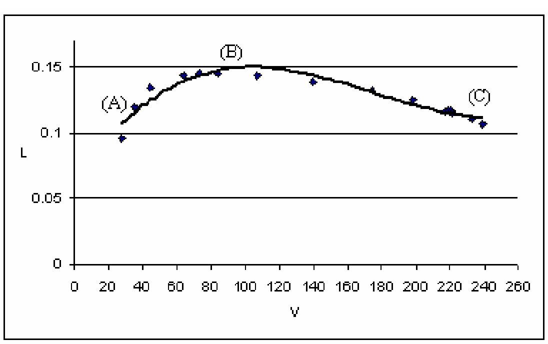

Figure 4: Variation of Magnetising Inductance with Voltage.

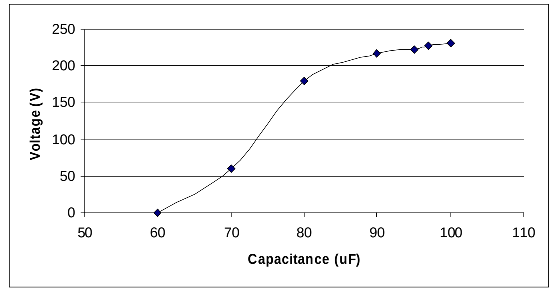

Figure 5: Relationship between terminal voltage, and parallel connected capacitance at 1500rpm.

the motor terminals will vary because of speed changes in the induction motor rotor, or voltage droop caused by electrical loading applied to the motor terminals.

Figure 5 shows the relationship between generator terminal voltage and connected capacitance, operating at a constant motor speed. Experimentally, it was found that the capacitance required to achieve 220VAC output at 1500rpm was 92μF. This is slightly greater than the 87μF determined previously for 50 Hz resonance, which is to be expected since the motor is running at slight negative slip under these conditions, and hence the output electrical frequency is slightly less than 50Hz. Figure 6 shows the AC waveform achieved under these conditions, which shows some level of harmonic distortion but is clearly quite acceptable.

Figure 7 shows the variation in capacitance required to maintain a constant output voltage as the load varies, still with the motor running at a constant 1500 rpm. It can be seen that this relationship is approximately linear.

The responses in both Figure 5 and Figure 7 are monotonic – an increasing capacitance either causes an increasing output voltage magnitude, or is required to maintain a constant output voltage as the load increases. Hence a suitable control strategy for voltage regulation is to measure the output voltage, and simply switch capacitance in or out of circuit as required to maintain a constant voltage.

Figure 8 and 9 show the change in AC voltage as 20 μF of capacitance is switched into and out of circuit. It can be seen from these figures that the generator response to an excitation change is not instantaneous, and that the resonant voltage changes gradually over several AC

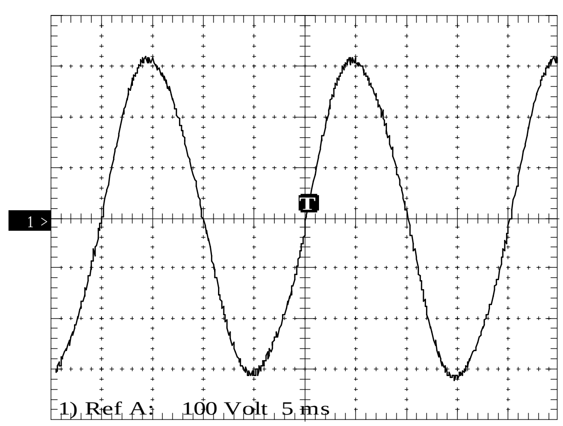

Figure 6: Steady-state AC voltage at 1500 rpm with 92μF excitation capacitance.

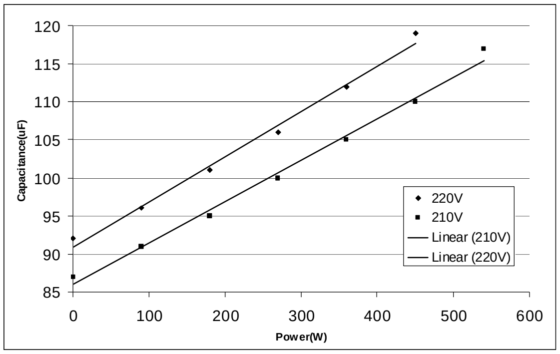

Figure 7: Capacitance required to maintain constant terminal voltage at constant speed as the load varies.

cycles to a new stable value after the step change in connected capacitance. It is noted that the influence of this delay will have to be accommodated by the voltage regulation control circuitry, and that the time constants involved are quite slow. Hence a digital microprocessor solution is most likely the preferred approach for a controller, since it can easily be used to implement voltage control algorithms of differing degrees of complexity, with whatever time delays are required.

From these results, it was identified that voltage regulation within ±0.5% of nominal voltage should be achievable if the capacitors are controlled with a resolution of 1µF.

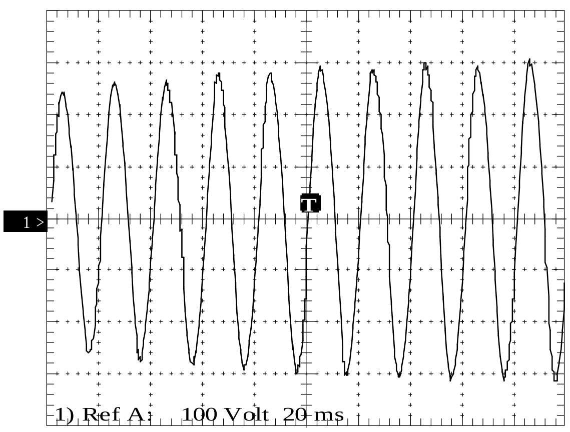

Figure 8: Change in output voltage as excitation capacitance is switched from 72µF to 92µF.

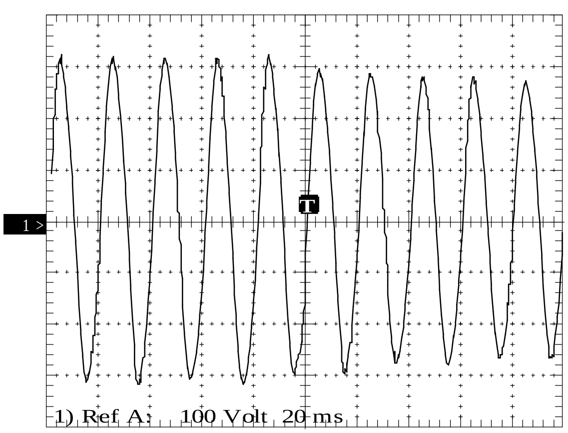

Figure 9: Change in output voltage as excitation capacitance is switched from 92µF to 72µF.

3.2. FREQUENCY REGULATION

Simple induction machine theory identifies that as the electrical load on an induction generator varies, the slip will also vary (as a function of rotor current). Figure 10 shows this effect, where the change in electrical output frequency can be seen as the electrical load is varied from 0W to 500W. For small slip conditions, the frequency variation is almost linear with load, as shown in Figure 10.

Hence an appropriate control strategy for the system is to vary the electrical load to maintain a constant output frequency. This is done using a phase controlled resistive dump load, which can be used to heat or boil water, charge batteries, or any other non critical load application that can be off loaded as required when a higher priority load comes on line.

4. CONTROL SYSTEM DESCRIPTION

The controller comprises a low cost microprocessor that uses triacs to switch capacitors into and out of circuit, and a phase controlled triac regulator to control the power supplied to a dump load resistor. Figure 11 shows the general system structure.

The system has two control loops, one regulating the AC voltage by varying the switched-in excitation capacitance, and the other regulating frequency by changing the firing angle of the phase controlled triac that feeds the dump resistor. The parameters of these control loops vary with the speed of the prime-mover, and hence the regulating circuit is rated for operation in the range 1500 – 1560 rpm, and for loads up to 500W. (The maximum output power of the generator is constrained by the rated current, which increases as the capacitance is increased).

The voltage regulating circuit is required to maintain a nominal output of 220VAC at 50Hz. To achieve this, there is a fixed capacitance for self-excitation of the generator, and smaller capacitances which are switched in a binary sequence to maintain constant output voltage over the operating range. The controller was designed with links for extra fixed capacitors, so that the system can be 'tuned' to suit a given generator.

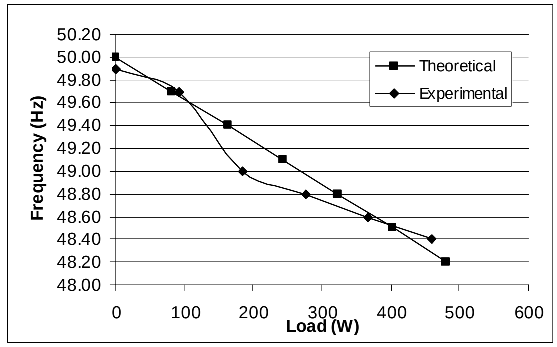

Figure 10: Variation of output frequency with load, operating at constant mechanical rotor speed.

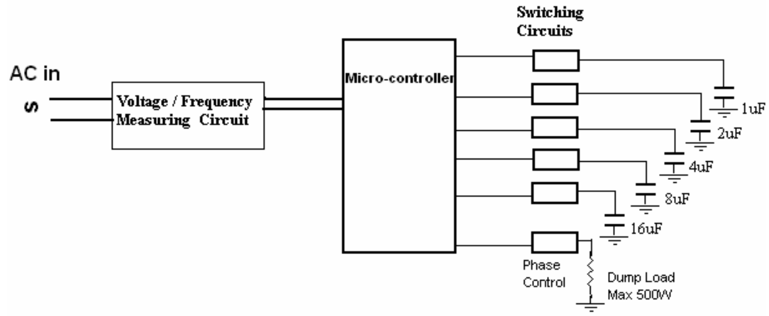

Figure 11: General arrangement of the proposed self-excited induction motor control system.

5. CAPACITOR SWITCHING

A particular challenge with this system was to arrange for the capacitors to be switched into the circuit without creating a significant current surge that would damage the triac switches. The elegant solution that was developed was to use a diode/resistor network to maintain the capacitor voltage at the AC voltage peak when the capacitor was not in circuit, and to switch on its associated triac as the generator voltage passes through its peak. This avoids any capacitor inrush surge current. Figure 12 shows the circuit concept.

Of course, this solution relies on the controller accurately switching the triac at the AC voltage peak, but this is not difficult using a microprocessor. Furthermore, any slight errors in switching have minimal impact on transients when switching at peak voltage, since the gradient of a sinusoidal waveform is at a minimum at its peak. Figures 13 and 14 shows the voltage and current switched waveforms for 25 μF of capacitance switching in and out of circuit, and there is no sign of any current inrush surge, as expected.

6. SYSTEM EXPERIMENTAL PERFORMANCE

An experimental system was constructed to verify the controller concepts presented in this paper, based around a DC load motor controlled by a variable speed drive system (representing the micro hydro turbine), driving into a 1kW single phase induction motor coupled to the DC motor shaft. The DC motor drive system was set to have a 6% speed droop over the load range 0 to 500W, to represent the expected load speed droop of a typical microhydro turbine of this power range. The experimental controller was constructed to operate as a self contained standalone system, powered from the self excited output of the induction generator.

Reliable excitation of the system is achieved by virtue of a push-button in series with the LC circuit, which must be pressed by an operator in order for startup to occur. The microcontroller then 'latches' on the circuit with a triac switch, and can disconnect the system in the event of an overvoltage fault or system instability.

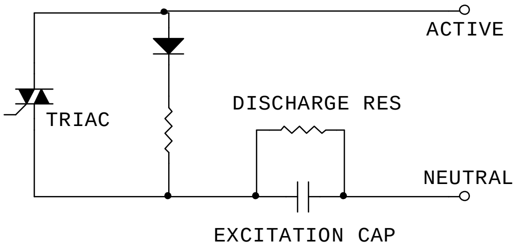

Figure 12: Capacitor switching circuit.

The controller regulation of the AC output frequency and voltage were investigated for two different loading conditions. Firstly, the motor shaft speed was varied using the DC drive system with the AC motor feeding into constant resistive load. Secondly, the load on the AC motor was varied over the range 0 to 500W, with the DC drive system set to a constant no-load speed set point. The experimental results obtained are as follows:

6.1. AC OUTPUT REGULATION WITH SPEED

Figures 15 and 16 show the controller's performance as the motor speed was varied over the range 1500rpm to 1560rpm, for the unregulated, simulated, and experimentally controlled cases. From these figures, it can be seen how the regulator closely maintains a

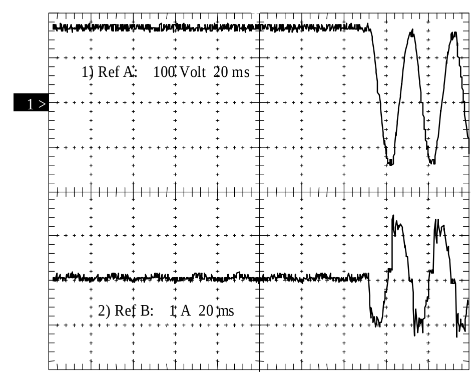

Figure 13: Capacitor voltage and current as 25 μF is switched into circuit.

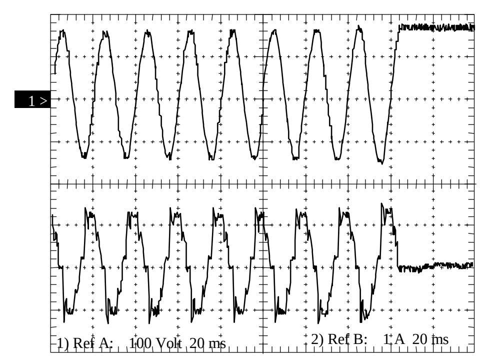

Figure 14: Capacitor voltage and current as 25 μF is switched out of circuit.

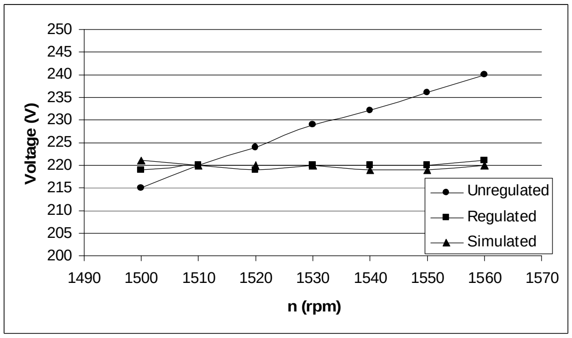

Figure 15: Experimental voltage variation with Speed.

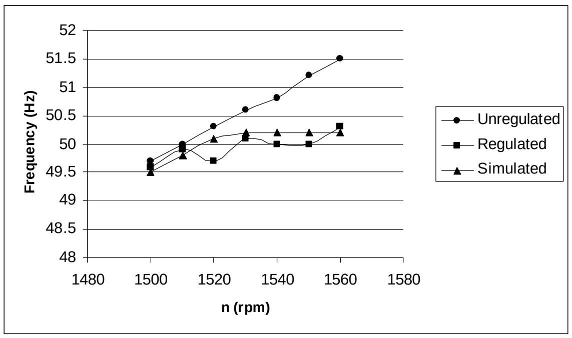

Figure 16: Experimental frequency variation with Speed.

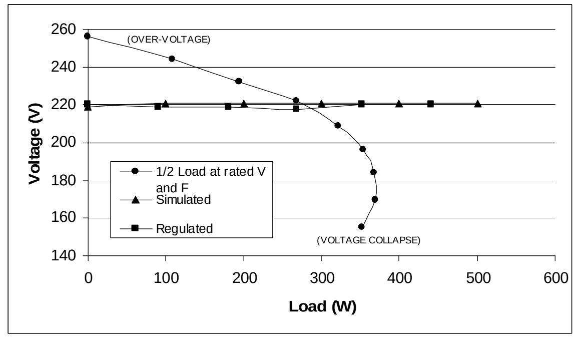

Figure 17: Experimental voltage variation with Load.

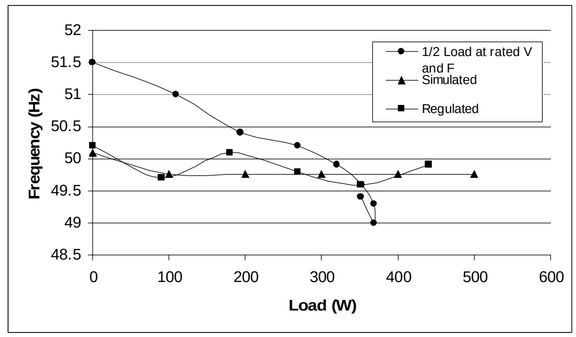

Figure 18: Experimental frequency variation with Load.

nominal 220V 50Hz output as the system speed varies, by varying the power fed to a resistive dump load, and switching capacitors into or out of circuit as required. (The slight difference between simulated and experimental output frequency is because of quantisation in the experimental frequency measurements.)

6.2. OUTPUT REGULATION WITH LOAD

Figures 17 and 18 show the system performance with varying load, where it can be seen how, as the system load increases, the regulator maintains system voltage and frequency by reducing power fed to the resistive dump load, and again switching capacitors into or out of the circuit as required. Results are once more shown for the unregulated, simulated and experimentally controlled cases. It can be seen that for the unregulated case, the voltage and frequency vary considerably from their nominal values as loading conditions vary, while in contrast the experimental controller is able to maintain the AC output within the range 219±1V at 49.9±0.3Hz as the load varies over the range of 0 to 450W (a minimum of 50W is fed to the dump load during system operation).

7. CONCLUSIONS

This paper has presented a cheap and robust micro-hydro generation system based on a single phase induction motor, which can regulate voltage to 219±1V and frequency to 49.9±0.3Hz as the system load increases from 0 to a maximum design limit of 500W. The system uses switched excitation capacitors to regulate the AC voltage, and a phase controlled resistive dump load to regulate the AC voltage and frequency, as load conditions and the energy available from the prime mover micro hydro turbine vary. The controller is based around a low cost microprocessor, which has the further advantage of allowing flexible control strategies to be easily implemented and tuned to suit any particular induction generator and prime mover system.

8. REFERENCES

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