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Induction Generator Control and Monitoring System for Micro-hydro Power Plants

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Abstract

The study is concerned with the evaluation of the performance of a locally made Induction Generator Control and Monitoring System (IGCMS) for micro-hydro plants implemented using mark-space ratio technique in low-cost microcontrollers. The heart of a micro-hydro power plant is the generator, the device that converts mechanical energy into electrical energy. Most commonly used generators are the Synchronous generator (SG) and the Induction generator (IG). Induction generators have the advantage of being cheap, readily available, and robust. However, the difficulty in determining its capacitance requirements and of controlling its generated voltage and frequency under varying loads present major challenges. This paper proposes the use of low cost microcontroller based induction generator load control and monitoring system employing mark-space ratio technology. Results showed this to be a comparatively accurate and economical means of controlling micro hydro generators.

Keywords: micro-hydro power plants, induction generator control and monitoring system, mark – space ratio

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1. Introduction

According to International Resources Group (IRG) / United States Agency for International Development (USAID) (2011), the Philippines being an archipelago has an abundant supply of hydropower resources. National Renewable Energy Laboratory (NREL) (2000), assessment shows a number of these sites are located in Mindanao, especially in Regions 9, 10 and 11. Figure 1 shows a typical micro hydro power plant scheme.

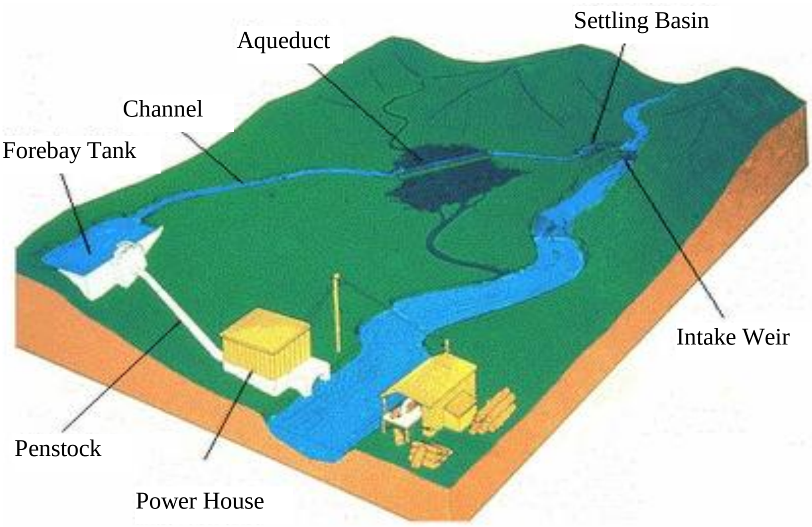


Figure 1. Typical micro-hydro power plant scheme

It is possible to develop these sites using locally made or available electro-mechanical and electronic equipments. One of them is the induction generator. Induction generators are relatively cheap, have components that are readily available, and are robust. However, there are two main challenges of using induction generators: capacitance requirements and control of its voltage and frequency. Although capacitive requirement is an important matter, it is beyond the scope of this study and thus, not be treated here. The second challenge concerning voltage and frequency control is discussed in detail in the following sections.

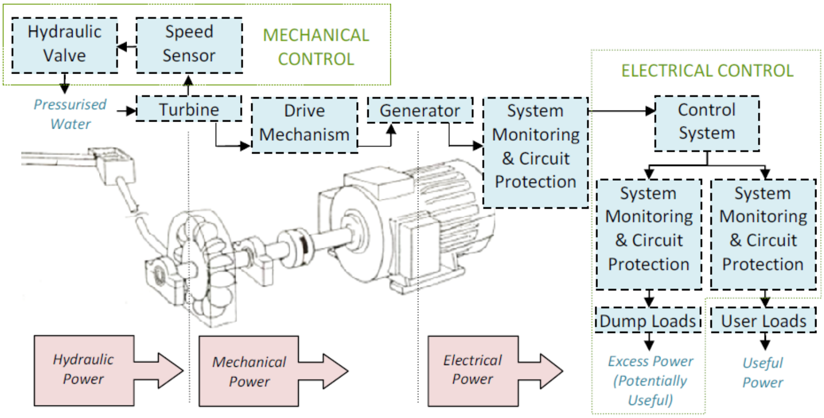
Hydro power plants are categorized by different organizations in different ways. However, NREL is credited to have first coined the word pico hydro. A new entry in the hydro power plant category is pico-hydro power plant. Pico hydro power plants are systems with a maximum of five kilowatts capacity. This means that today, due to an increasing demand for electrical power and the advancement of technology, whatever power is practically available is can be utilized. Table 1 shows classification of hydro power plants according to capacity and according to available head.

Table 1. Classification of hydro power plants

Classification according to its capacity (watts)	
Pico-hydro	up to 5kW
Micro-hydro	5-kW to 100kW
Mini-hydro	above 100kW to 1MW
Small-hydro	1MW to 15MW
Medium-hydro	15MW to 100MW
Large hydro	more than 100MW
Classification according to head	
Low head	less than 10 meters
Medium head	10 to 50 meters
High head	above 50 meters

Source: H. Luden, "Electronic Load Controller for Micro-Hydro Systems", Accessed: 10 November 2011

Mbabazi and Leary (2010), have suggested that control of micro hydro power plants can be put into three categories: Mechanical (turbine control), electrical (generator control), and electronic (load control). Figure 2 shows a diagram of these three types of control.



Source: International Resource Group/ USAID, Philippines Country Report, June 2007

Figure 2. Mechanical and electrical control of a micro hydro system

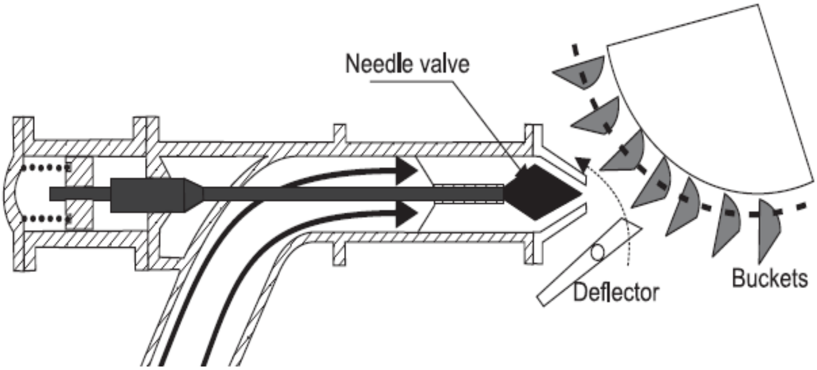
Mechanical (turbine) control consists of mechanical systems to control the input of hydraulic power into the turbine by various means. By controlling the water flow rate, Q into the turbine, mechanical power is controlled. This is expressed by

$$P_{mech\ (turbine)} = \rho Q g H_{net} \quad (1)$$

where

ρ = density of water, 1000kg/cu.m
Q = discharge of water, cu.m/sec
g = gravitational acceleration, 9.81 m/s^2
H_{net} = net available head, m
P_{mech} = available mechanical power, Kw

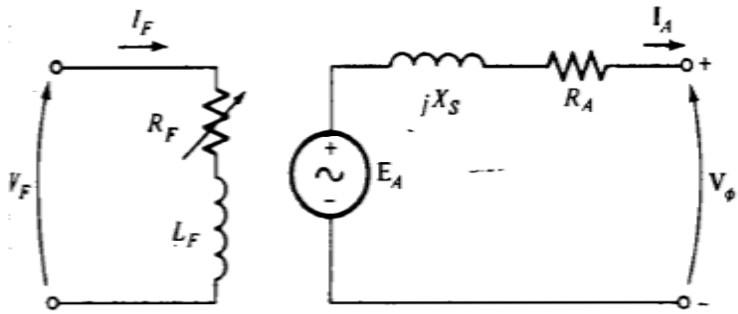
One example of mechanical control is shown in Figure 3, the control of Pelton turbines. According to Penche (1998), Pelton turbines use moving needle valves to control the nozzle jet area. Another is the control of Francis turbines which use movable vanes to control the volume of water input into the turbine thereby controlling mechanical power (Kjolle, 2001). Thus, in order to obtain a steady state condition, mechanical power supply should be equal to the variable electrical power demand. However, for micro hydro schemes this means of control is considered slow, expensive, and maintenance extensive.



Source: J.B. Ekanayake, "Induction Generators for Small Hydro Schemes", 2002

Figure 3. Pelton turbine needle valve mechanical control scheme

Electrical (generator) control consists of controlling generator voltage and frequency. A number of schemes have been proposed. For SGC, Automatic Voltage regulator (AVR) controls the voltage by controlling the field flux (Chapman, 1998). This is illustrated in Figure 4.



Source: N.K. Smith, “Motors as Generators for Micro-hydro Power”, 2001

Figure 4. Synchronous Generator field flux voltage control schematic diagram

This can be shown by

$$E_{gen} = P\O NZ \tag{2}$$

where

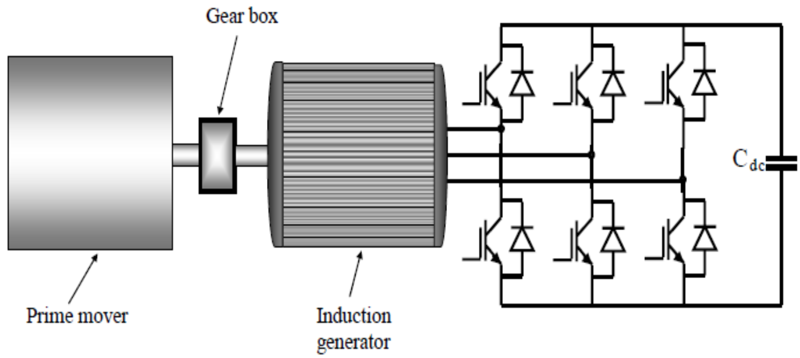
Frequency is controlled by controlling the speed of the prime mover by mechanical means. This is shown by

$$f = \frac{P}{2} \cdot \frac{N}{60} \tag{3}$$

where

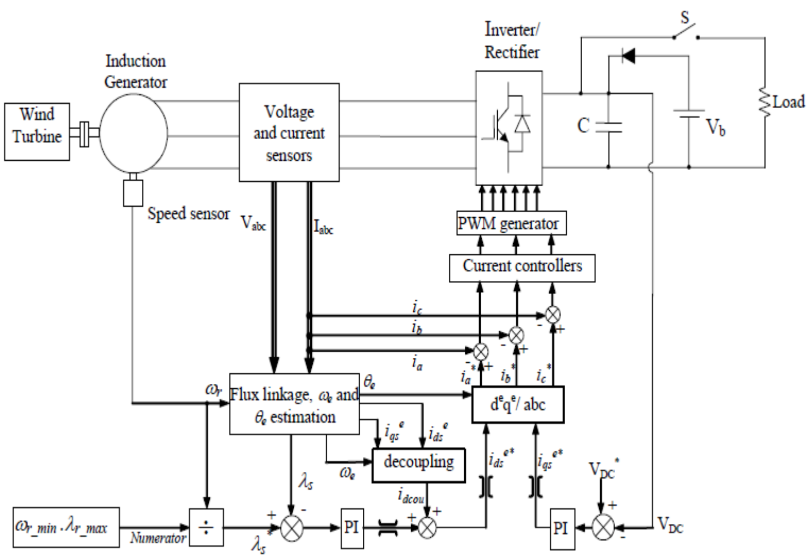
f = frequency, Hz
P = number of generator field poles
N = generator speed, rpm

The present technology for Induction Generator Control (IGC) can be categorized into two main categories: scalar control and vector control. As of now, these are still economically and even technologically unjustifiable for employment in micro hydro power plants because they involve very complex computer programs and expensive (and often unavailable) electronic devices to implement. Figure 5 and Figure 6 illustrate a vector control scheme.



Source: NREL, Assessment of the Micro Hydro Resources in the Philippines, October 2000

Figure 5. Illustration of vector voltage control scheme for induction generator



Source: NREL, Assessment of the Micro Hydro Resources in the Philippines, October 2000

Figure 6. Stator oriented vector control connection scheme

Electronic (load) control provides the most economical and technologically reasonable means of micro hydro power plant control. This scheme controls the generator voltage and frequency by making the load to appear constant to the generator. This is shown in Figure 7.

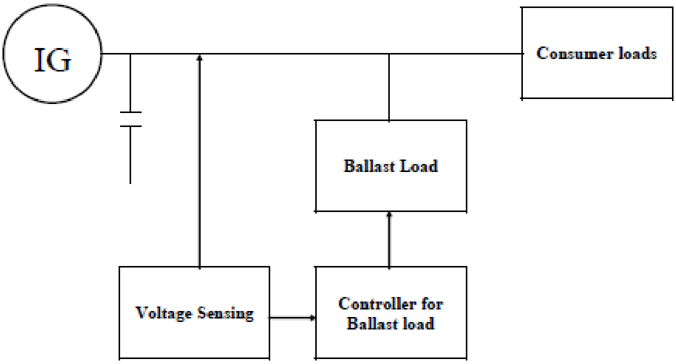
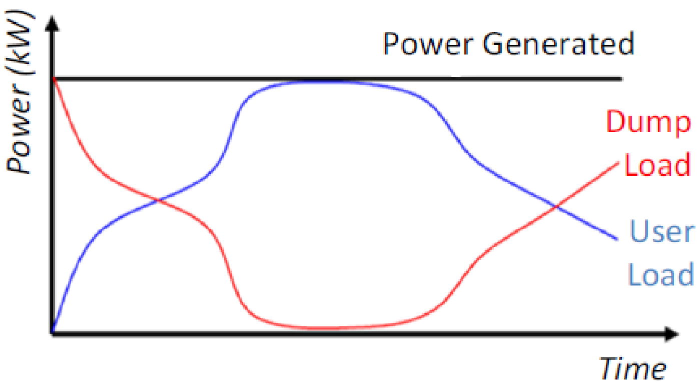


Figure7. Induction generator load control scheme

This scheme is achieved by putting "ballast or dump" loads in parallel with the main load. The ballast load increase when the main load decrease, and it will decrease when the main load increase, thus maintaining the total load to be equal to the maximum allowable generator load. This is illustrated in Figure 8 and expressed by (4).

$$P_{gen} = P_{main} + P_{dump} = P_{constant} \qquad (4)$$



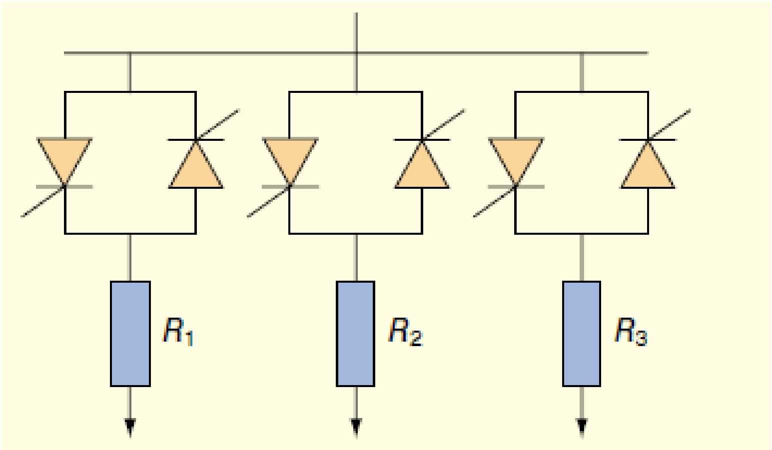
Source: International Resource Group/ USAID, Philippines Country Report, June 2007

Figure 8. Graph of user load and dump load power consumption

A number of schemes have been proposed for Electronic Load Controllers (ELC), each with its own advantage and disadvantages. Three of which are discussed in this section.

Mbabazi and Leary (2010), have made a comparative study of existing schemes. Among the schemes mentioned, two are prominent, the *Hummingbird* and *Homo Luden's ELC.* Hummingbird uses a stepped resistance control while H. Luden's ELC uses phase angle control. Schematic diagrams of these schemes can be found in J. Portegijs (2000) and H. Luden (2011).

Stepped load control is illustrated in Figure 9. In this scheme a combination of different ballast resistance are switched on or off depending on main load variations to maintain the total load constant. This scheme has been implemented but, being stepped, it was found not able to completely control small deviations falling in-between its stepped values.

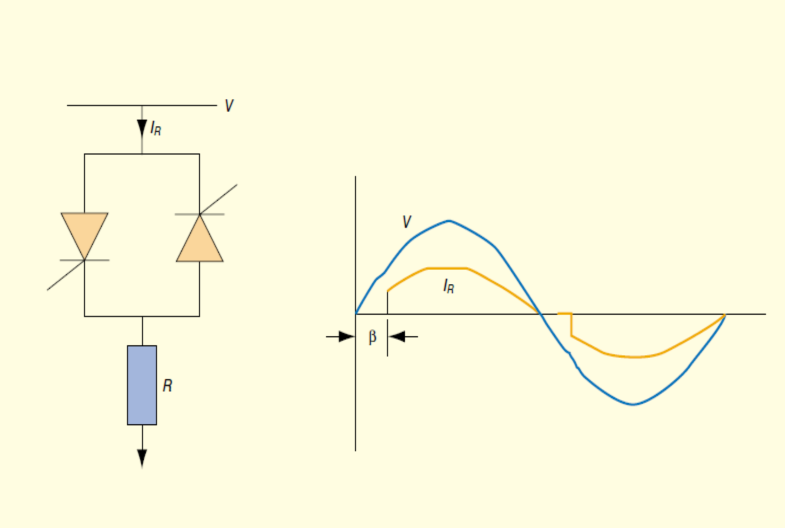


Source: S.S. Juca, 2011

Figure 9. Illustration of stepped load control

Phase angle control controls the amount of current passing through a fixed ballast load, hence producing a variable load effect that is not steeped by incremental. This is illustrated in Figure 10.

This type of control is finer than the stepped load control; however, this control has its drawback. From Figure 10, it can be seen that the controller current lags its voltage. This shows that the controller has a lagging power factor. The power factor of load will be affected by the lagging power factor of the controller. Moreover, the generator will also be affected by this inductive characteristic.



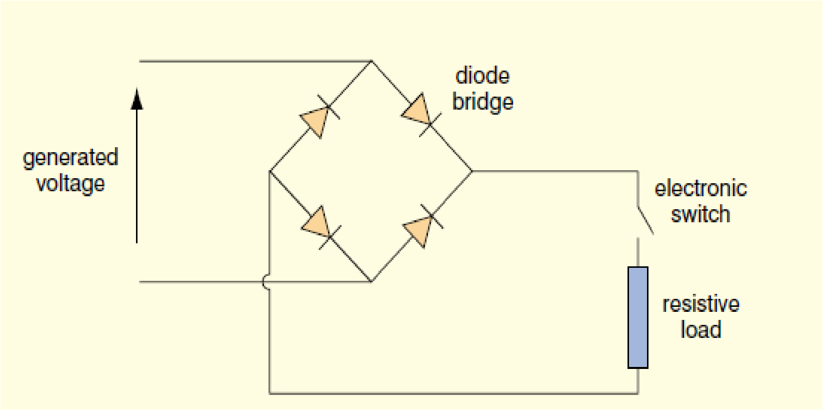
Source: S.S. Juca, 2011

Figure 10. Illustration of Phase Angle Control scheme

This will absorb the capacitance in the generator which is provided by capacitors, thereby affecting its excitation flux and generated voltage. Thus this type of control is not very much suitable for induction generators.

Mark-space ratio control was proposed by N. K. Smith (2001) from Nottingham University, UK. This concept is illustrated in Figures 11, 12 and 13. This control first rectifies the generator output voltage before it is applied to the ballast load. This insures that there would be no difference in power factor between the ballast load and the main load thus providing a better quality generator output voltage. Graphical representation of the ballast load voltage is shown in Figure 12 and that of the main load is shown in Figure 11.

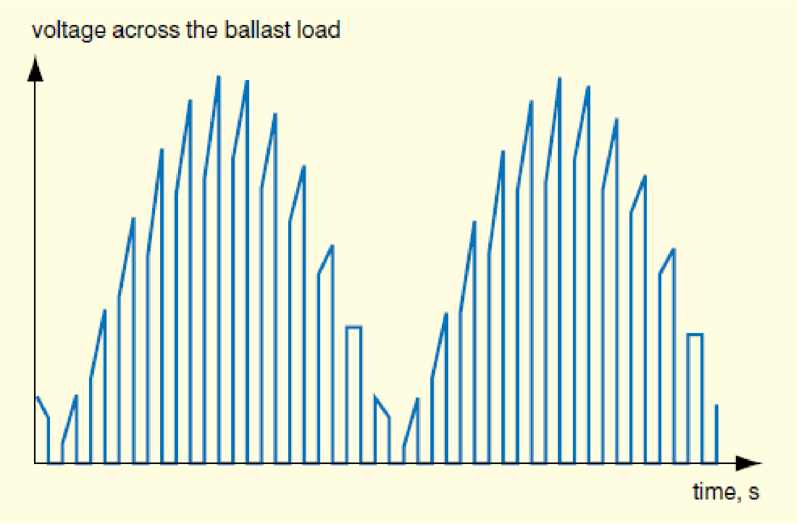
Figure 11 shows that the generated voltage is rectified first before it is fed to the resistive ballast load through an electronic switch. The electronic switch is turned on and off depending on load changes. If the load increases, the ballast load must be decreased and so the “off” time or “space” of the switch should be longer. The reverse is true if the main load decreases. Figure 12 shows the output wave form across the ballast load.



Source: S.S. Juca, 2011

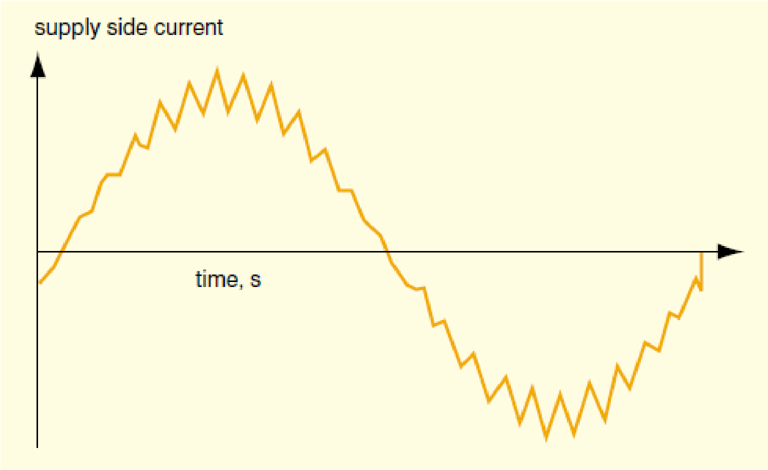
Figure 11. Mark-space ratio control scheme

The whole process is made possible by fast micro controllers that control high speed switching circuits for the electronic switches like the Insulated Gate Bipolar Transistor (IGBT). Figure 13 shows a typical output wave form from an induction generator.



Source: S.S. Juca, 2011

Figure 12. Voltage waveform across the ballast load



Source: S.S. Juca, 2011

Figure 13. Voltage waveform across the generator

In this study, the scheme proposed by N. K. Smith (2001), called the mark-space ratio control, was implemented using low cost and modular microcontrollers. This is because Smith's scheme is more reliable, has better load voltage quality, simpler design, easier to implement, and thus, more economical. Although the literature mentioned proposed and implemented this scheme, no practical circuit was given. Thus, this study used the scheme but provides an altogether new method of implementation by using low cost modular microcontrollers and electronic devices.

Generator voltage, speed, frequency, current, and power have to be constantly monitored to ensure normal operation of the plant. Failure to monitor these parameters can cause abnormal conditions to arise and thereby cause damage to the generator and other devices.

Monitoring equipments can be classified into conventional and electronic based. There are standard conventional monitoring equipments, like panel mounted voltmeters, ammeters, watt-hour meters that could be used for micro-hydro power plants, however they could too expensive for small applications. Electronic based monitoring equipments are compact and low-cost and are thus suitable for small applications. They are also capable of data acquisition. Advances in micro controller and sensor technologies have developed low-cost devices capable of monitoring, control and data acquisition. They could be assembled into compact and easily installable systems. Moreover, they are also locally available. With these technologies it is possible not only to display in one LCD all the monitored plant parameters but also to store and communicate them. S. S. Juca (2011), has done a review of literature related to these technologies, especially applied to PV and wind systems.

The objective of this study is to develop a locally made induction generator load controller that is low cost, reliable and easy to build and maintain, and which has the following capabilities: (1) control the magnitude and frequency of the generated voltage under variable load conditions and; (2) monitor the generated voltage, frequency, current, power, and generator speed.

This study can be a significant contribution to the development of micro hydro power plants for rural electrification which aids to contain the present energy crisis in Mindanao. One of the novel features of this system is the incorporation of control and monitoring. Not only are the voltage, current, frequency, power, and speed controlled, but they are also monitored. Another feature is the employment zero crossing technique. This technique eliminates the use of mechanical systems of monitoring speed which can be bulky and maintenance extensive. Lastly, because there are no known locally available literature or product of this type of device so its implementation can also be considered a novelty.

2. Methodology

Generally, three major steps were taken in developing the IGCMS. The first was to develop the control system and the second was to develop the monitoring system and the third was to integrate them together. The details of this process are shown Figure 14, which is a flow chart of the development process.

The control and monitoring objectives are: (1) to control the generator voltage and frequency within tolerable values under variable load conditions; (2) to achieve control of the induction generator voltage and frequency electronically using the mark-space ration technique; (3) to implement this scheme using low-cost microcontrollers and electronic devices and; (4) to monitor the generator voltage, frequency and power.

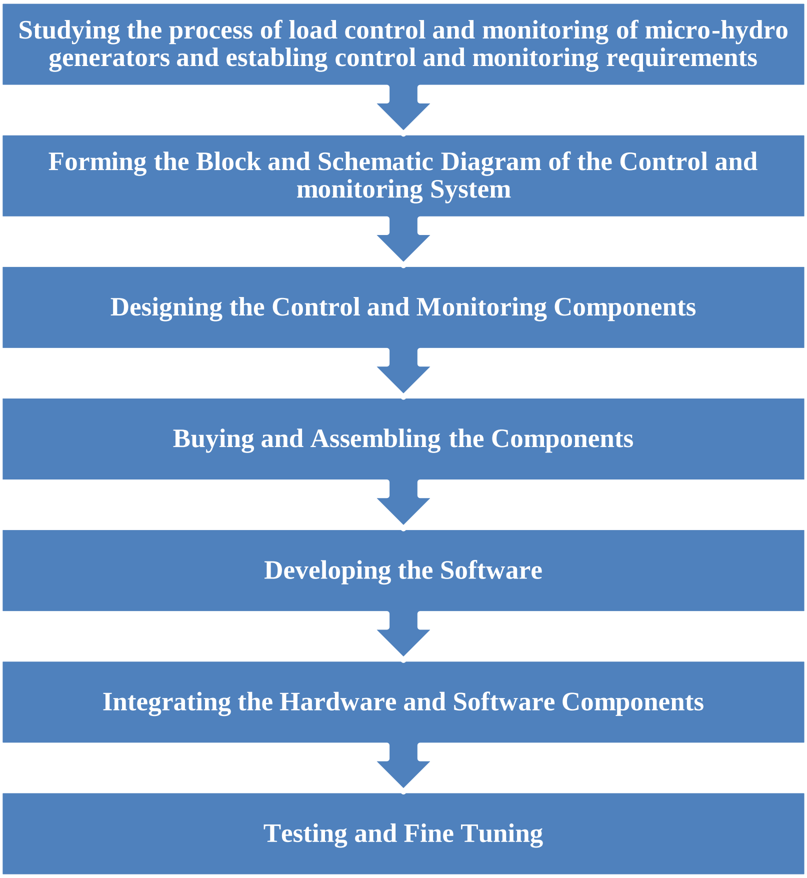


Figure 14. Flow chart of the process of developing the IGCMS

Figure 15 shows a schematic diagram of the control system. The Induction Generator (IG) is connected to the load and control system through a Circuit Breaker (CB). This is used to protect the system from short circuits and to provide a disconnecting means for the generator from the rest of the circuit. The control system comprises the Potential Transformer (PT), the rectifier diodes D1 and D2 with their corresponding voltage conditioning circuits V1 and V2. The conditioning circuits provide the power supply and the control signal to the Microcontroller Unit (MCU). The microcontroller controls the gate circuit of the transistor IGBT. The IGBT or insulated gate bipolar transistor is responsible for the mark-space control characteristic. It switches on and off the direct current supplied by the rectifier D3 to the dump load DL. Figure 16 shows a picture of the control system developed.

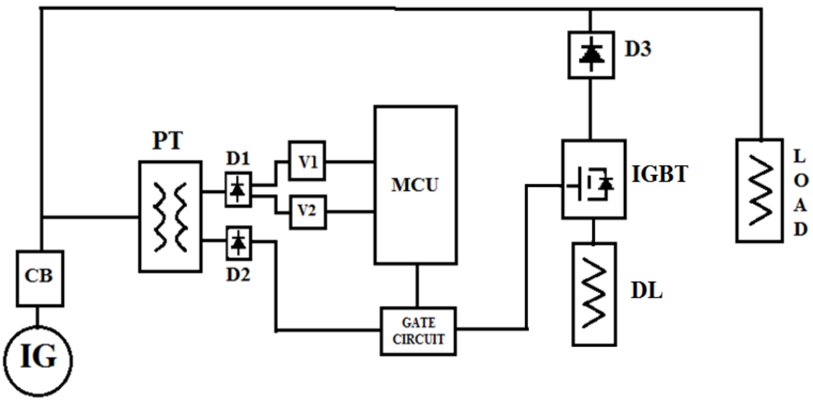


Figure 15. Schematic diagram of the IGCS

Figure 16. Picture of the developed IGCS

Figure 17 shows the schematic diagram of the monitoring system. The Potential Transformer (PT) extracts the voltage from the transformer and at the same time supplies the power to the microcontroller. CT extracts the current from the generator. Both the voltage and current signals were conditioned to standard levels before being fed to the microcontroller. The microcontroller then processes these signals for display in the LCD or liquid crystal display and data logging in the SD card.

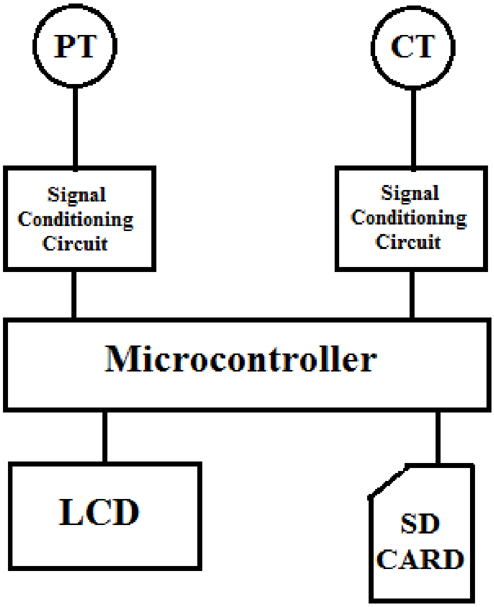


Figure 17. Schematic diagram of the IGMS

Basically, the power in watts is a derived unit. It is the product of the system voltage, current, and power factor. This is expressed in (5).

$$P = VI\cos\Theta \tag{5}$$

where

P = the power, watts
V = the system voltage
I = the current
θ = is the angle between the voltage and current
$\cos\ \theta$ = the power factor

Figure 18 shows the integrated control and monitoring systems. This is now the induction generator control and monitoring system or IGCMS. The Ground Fault Circuit Interrupter (GFCI) protects the system and personnel from accidental ground faults.

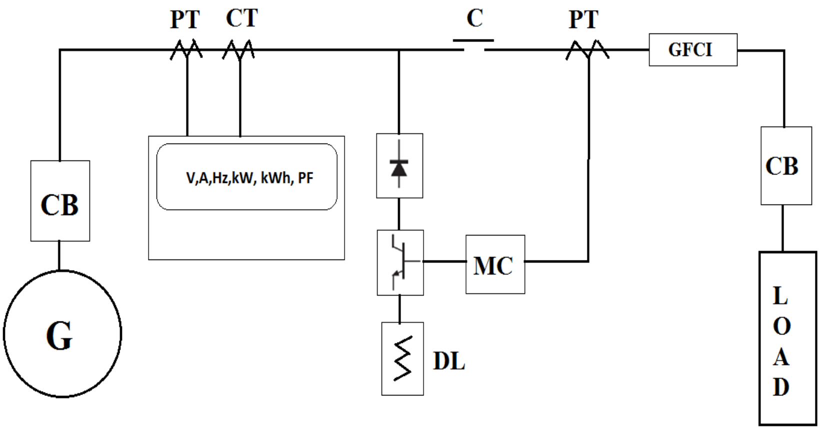


Figure 18. Schematic diagram of the developed IGCMS

Figure 19 shows a picture of the circuit board and Figure 20 is the display of the monitoring system.

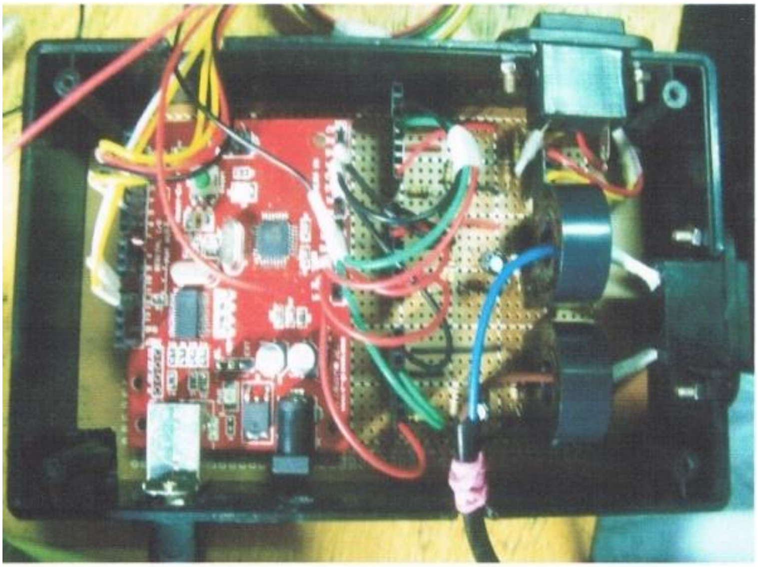


Figure 19. Circuitry of monitoring system developed

Figure 20. Display of the monitoring system

After the whole system has been assembled it is then ready for testing and fine tuning. Figure 21 shows the laboratory set up of the system. Figure 22 shows the system under test.

Figure 21. Laboratory set up of the IGCMS

Figure 22. IGCMS under testing and fine tuning

3. Results and Discussion

Figure 23 shows an oscilloscope display of the characteristic induction generator load controller output voltage. This is very much identical to the ideal output in Figure 12 for systems that employ mark-space ratio technique. This controller voltage supplies the ballast load. This waveform illustrates the effectiveness of the developed controller.

Figure 23. Characteristic output voltage waveform of mark-space ratio controller

Two of the most important parameters that determine the quality of electrical power generated are voltage magnitude and its frequency. In the Philippines Grid Code (2001) specified it to be 220 volts and 60 hertz for general household use. Tolerable limits for voltage is $\mp 10\%$ and $\mp 3\%$ for frequency. Furthermore, electrical devices and appliances are rated to these values. It is important therefore to limit the generator voltage and frequency to these values. Figure 24 shows the magnitude of the generated voltage under load changes. It can be seen from this figure that the generated voltage is 227 volts at no load and drops to around 220 volts during various load changes.

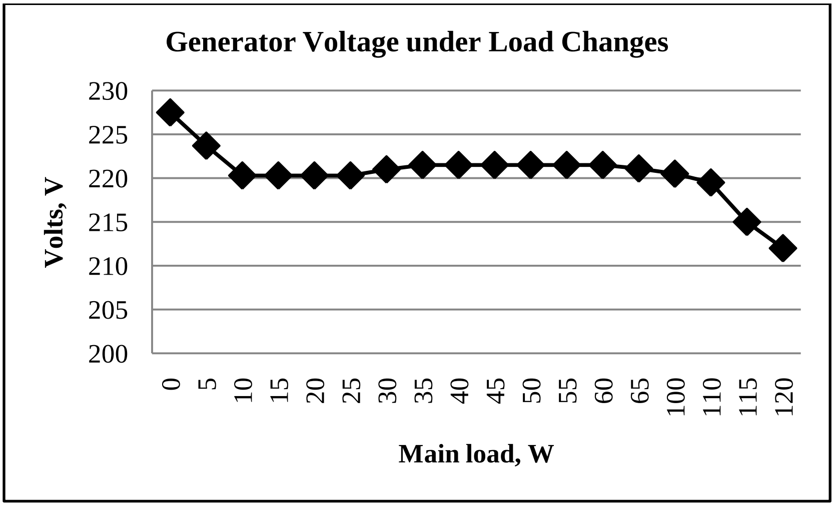


Figure 24. Generated voltage under variable load condition

Figure 25 shows the variation of the generator frequency under load changes. As can be noticed in Figure 25 the frequency falls below tolerable limits this is because the available prime mover is rated lower than generator rating and the speed conversion mechanism used is inferior.

In this study, the available prime mover is only 1 kilowatt. This is less than the generator rating of 1.5 kilowatts. Even with these deficiencies in the set up, the IGCS is still working to maintain the generator voltage within tolerable limits and frequency at very close to tolerable values under various load conditions. Both the voltage and frequency begin to decrease; however, as the prime mover power limit is being reached.

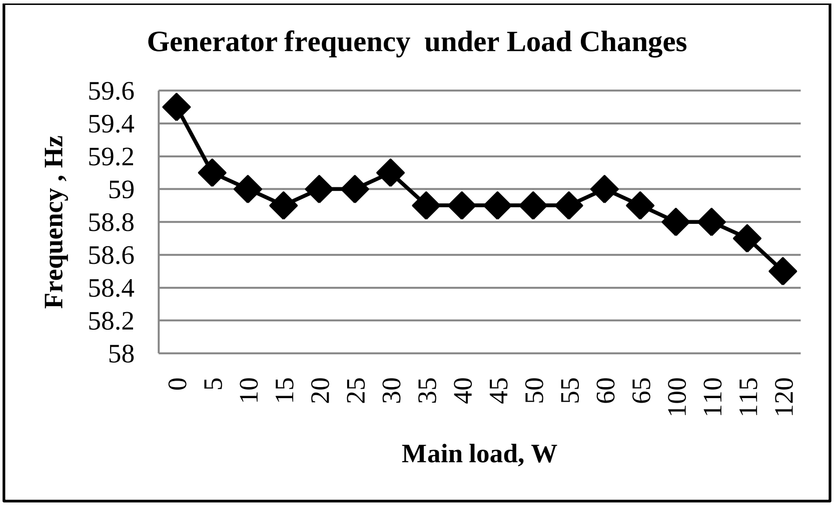


Figure 25. Generator frequency under load changes

Figure 26 shows the relative stability of the voltage and frequency under varying loads. Figures in the x-axis of the graphs are the step loads varying from 0 to 120 watts.

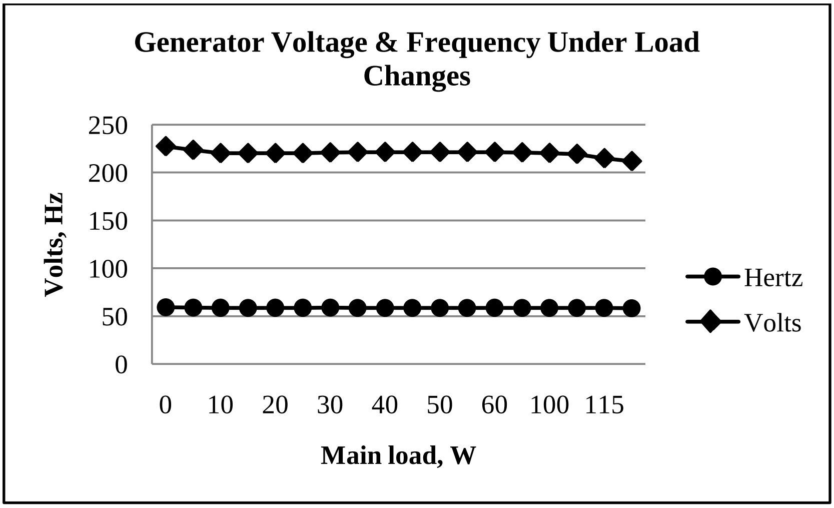


Figure 26. Generator voltage and frequency under varying load conditions

Figure 27 shows the relative changes of main load and dump load power. This is very much identical to Figure 8 and obtains the required characteristic that the dump load absorbs or sheds power as the main load decrease or increase power respectively. This shows that the control system developed has met the requirements.

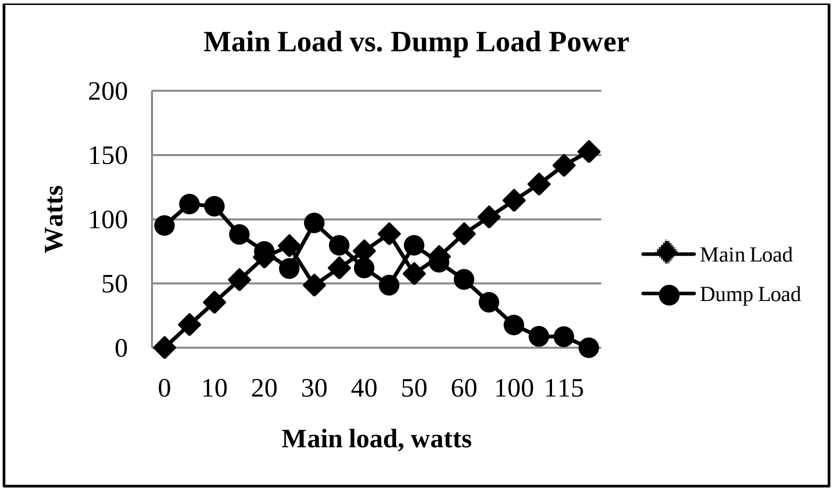


Figure 27. Characteristic mirror image of the main load vs. dump load power absorption

Figure 28 shows that the generator power is maintained constant under variable load conditions. From a no-load power of around 475 watts, it suddenly drops to around 140 watts as the loads are switched on. From then on, it is maintained around this value.

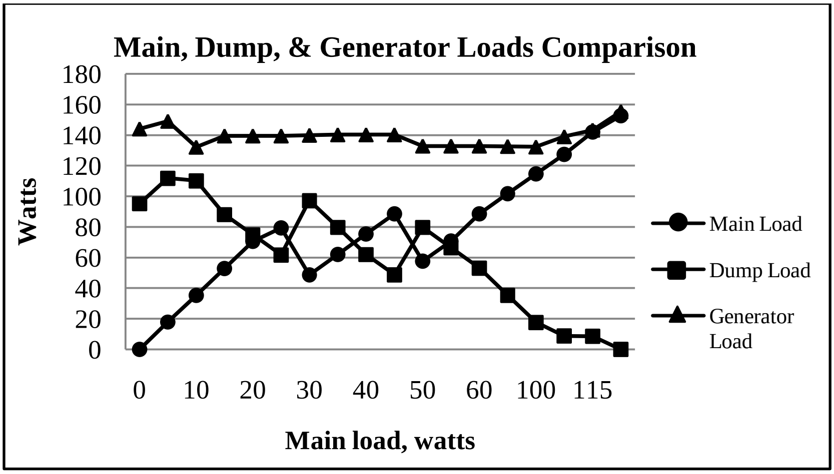


Figure 28. Comparison of the main, dump, and generator loads

Figure 29 shows the variation of generator speed as load changes. Generator speed and frequency are related according to equation (3).

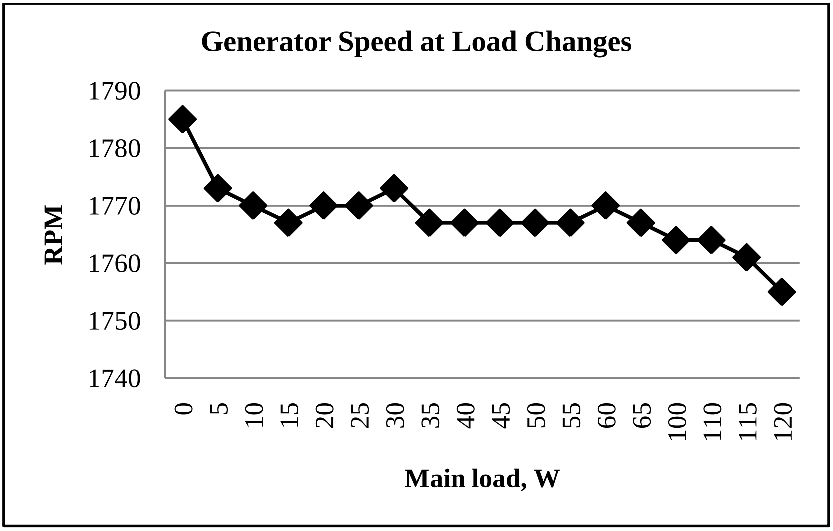


Figure 29. Generator speed at load changes

Table 2 shows the tabulated result of the monitoring system. It measures the voltage and current and calculates the power of the main load, the dump load, and the generator.

4. Conclusion and Recommendation

Based on the results presented, the attempt to control the voltage and frequency of the generator using a low cost controller was achieved and it showed relatively stable response under load changes. Through this, study has to come to the conclusion that locally made low cost microcontroller based induction generator load control and monitoring system employing mark-space ratio technology are comparatively accurate and economical means of controlling micro hydro generators.

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Table 2. Tabulated results of monitoring system.

Main Load				Dump Load			Generator				
Rating	Voltage	Current	Power consumed	Voltage	Current	Power consumed	Freq	Speed	Voltage	Current	Generated power
Watts	Volts	Amperes	Watts	Volts	Amperes	Watts	Hz	Rpm	Volts	Amperes	Watts
0	227.5	0	0	227.5	0.38	86.5	59.5	1785	227.5	0.63	144.1
5	223.7	0.08	17.9	223.7	0.5	111.9	59.1	1773	223.7	0.67	149.1
10	220.3	0.16	35.2	220.3	0.5	110.2	59.0	1770	220.3	0.60	132.2
15	220.3	0.24	52.9	220.3	0.4	88.1	58.9	1767	220.3	0.63	139.5
20	220.3	0.32	70.5	220.3	0.34	74.9	59.0	1770	220.3	0.63	139.5
25	220.3	0.36	79.3	220.3	0.28	61.7	59.0	1770	220.3	0.63	139.5
30	221.0	0.22	48.6	221	0.44	97.2	59.1	1773	221.0	0.63	140.0
35	221.5	0.28	62.0	221.5	0.36	79.7	58.9	1767	221.5	0.63	140.3
40	221.5	0.34	75.3	221.5	0.28	62.0	58.9	1767	221.5	0.63	140.3
45	221.5	0.4	88.6	221.5	0.22	48.7	58.9	1767	221.5	0.63	140.3
50	221.5	0.26	57.6	221.5	0.36	79.7	58.9	1767	221.5	0.60	132.9
55	221.5	0.32	70.9	221.5	0.3	66.5	58.9	1767	221.5	0.60	132.9
60	221.5	0.4	88.6	221.5	0.24	53.2	59.0	1770	221.5	0.60	132.9
65	221.1	0.46	101.7	221.1	0.16	35.4	58.9	1767	221.1	0.60	132.7
100	220.5	0.52	114.7	220.5	0.08	17.6	58.8	1764	220.5	0.60	132.3
110	219.5	0.58	127.3	219.5	0.04	8.8	58.8	1764	219.5	0.63	139.0
115	215.0	0.66	141.9	215	0.04	8.6	58.7	1761	215.0	0.67	143.3
120	212.0	0.72	152.6	212	0	0.0	58.5	1755	212.0	0.73	155.5

5. References

Arne Kjolle, (2001). Hydro Power in Norway: Mechanical Equipment, Norwegian University of Science and Technology, Trondheim, Norway.

British hydropower Association, (2005). "A Guide to UK Mini-hydro Developments".

Chapman, S.J., (1998). Fundamentals of Electric Machinery, 4th edition.

Ekanayake, J.B., (2002). "Induction Generators for Small Hydro Schemes", Power Engineering Journal.

Energy Regulatory Commission, "Philippine Grid Code". December 2001. page 78.

International Resource Group/ USAID (2007), Philippines Country Report, From Ideas to Action: Clean Energy Solutions for Asia to Address Climate Change, June 2007

Juca, S.S., (2011). "Low Cost Concept for Data Acquisition Systems Applied to Decentralized Renewable Energy Plants", Sensors, An MDPI Journal, www.mdpi.com.

Luden H., (2011). "Electronic Load Controller for Micro-Hydro Systems", Accessed: 10 November 2011, http://ludens.cl/electron/picelc.html

Mbabazi, S. and Leary, J., (2010). "Analysis and Design of Electronic Load Controllers for Micro Hydro Systems in the Developing World", University of Sheffield,UK.

NREL, (2000). Assessment of the Micro Hydro Resources in the Philippines - Final report, October 2000.

Penche, Celso, (1998). "Layman's Guidebook on How to Develop Small Hydro Site", European Small Hydro Association (ESHA), Belgica, Brussels.

Portegijs, J., (2000). "The Hummingbird", www.geocites.com.

Seyoum D., Rahman M.f., Grantham C., Mckinnon D., (2003). The Control of a Loaded Inverter Fed Isolated Induction Generator, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, Australia, AUPEC.

Smith, N.K., (2001). "Motors as Generators for Micro-hydro Power", ITDG Publishing, London.