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Combining Small-Scale Wind and Hydro Generation

Ibrahim Al-Bahadly, Zubair Rehman^{*}, Joshua Pirihi

School of Engineering and Advanced Technology Massey University, Palmerston North, New Zealand

^{*} Correspondence: z.rehman1@massey.ac.nz

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ABSTRACT

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COMBINING SMALL-SCALE WIND AND HYDRO GENERATION

Ibrahim Al-Bahadly, Zubair Rehman* & Joshua Pirihi

*School of Engineering and Advanced Technology
Massey University, Palmerston North, New Zealand*

**z.rehman1@massey.ac.nz*

www.nzaar.com

Abstract

Abstract— Renewable energy is a useful and significant source of electrical power, and its use is only increasing as the availability of fossil fuels dwindles. This work seeks to make renewable energy more reliable, cost effective, and accessible by exploring a different energy combination system to that currently applied to wind and hydro power. Instead of the usual electrical combination of wind and hydro generators, this project involved combining a water and wind turbine mechanically, before driving an electrical generator. This new combination system was modeled and optimized in MATLAB, using a direct combination system commonly found in multi-engine helicopters. The system was found to operate satisfactorily, however it is mechanically more complex than current, electrical combining systems. There is potential for further research in the areas of pump-hydro storage and using a water pump as a turbine, both as an extension of this project. Research was undertaken regarding wind and water resource availability, and the turbines were chosen with these taken into consideration. Various combination systems were explored, including torque and speed split mechanical combinations, conventional electrical combination, and using a modified switched reluctance generator as a method of electro-mechanical combination.

Keywords *Renewable Energy, Wind Turbine, Hydro Turbine*

1. Introduction

In traditional hybrid energy system energy obtained from different renewable energy sources is collected at a common DC bus [1]-[7] or these sources are connected electrically through power electronics interface [8]-[11] to extract maximum energy from the sources and for optimal use of harvested energy. In contrast to the traditional system of connecting renewable energy sources, this work involves designing and modelling a renewable electricity generation system whereby a small wind turbine and small water turbine are mechanically combined to drive a single generator.

All renewable energy applications are very dependent on site geography and resource availability. The available resources were researched and settled before choosing turbines and generators. Following that, various methods of combination are researched and discussed. The chosen system is then implemented using computer simulation software, and the output from the simulation is used to compare with

existing systems of combination. Finally, conclusions and final recommendations are drawn, and future developments are explained.

2. Application Context

The use of renewable energy technologies, both large and small scale, is largely dependent on the geography in the area of application. In order to simplify development, the project is directed towards a small-scale implementation. Typically, this will involve a rural property or lifestyle block, where the land owner has access to a source of flowing water, and steady wind. Based on an average household power consumption of 8000 kWh per year, this system will aim to generate approximately 1 kW on average. There is, however, argument for considerably less than that, because with some care and attention to energy efficiency power usage could realistically be half of that. Lifetime of the system is also considered while choosing the components and for this study it will be taken as 10

years. A factor of safety of at least 10 was applied when selecting or designing components.

Small scale renewable energy applications are inherently specific to the site they are implemented on. This makes it very difficult to research and design a system that can be generally applied. For this reason a suitable site has been assumed, with a source of hydro energy and wind energy in close proximity. Examples of such locations in New Zealand include valley floors facing into the prevailing wind (typically westerly), and mountain ranges such as the Ruahine and Tararua Ranges. Exposed coastal areas with streams could also suit. The specific parameters assumed for this study are:

- i) Water flow: 20 litres/sec, 5 metres head
- ii) Wind: 5-6 m/s on average, feasible to place a small wind turbine in clean air.

The wind speed was chosen based on information from NIWA [12]. Figure 1 illustrates the available wind resource for the whole of New Zealand. The water supply is deliberately a small estimate to maximize the applicability of this project to a wider selection of sites.

3. Wind Turbine Selection

3.1 Model Description

The Background choice of a wind turbine was between three possibilities, see table 1. The model given in [13] was analyzed and the following equation giving output torque as a function of shaft speed ω , was produced. Note that this works with normalized speeds and torques (i.e. expects ω in the range of 0-1 (1 being the rated wind velocity for the turbine), and gives the output torque in the range 0-1 (1 being the stall torque).

$$Torque = 0.0608\omega^3 + 2.1288\omega^2 + 0.5264\omega + 1.011 \quad (1)$$

With this equation in hand, the overall model for the wind turbine required for the

project was produced. It can be broken down as shown in Figure 2.

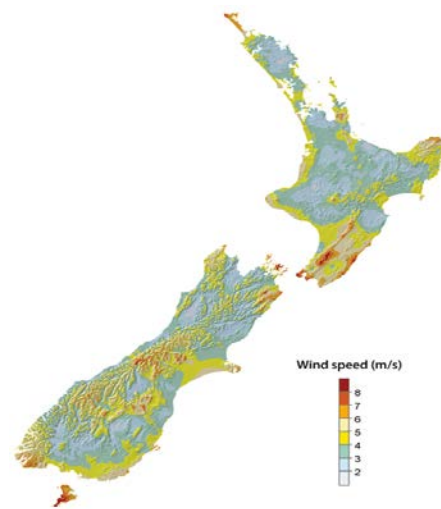


Figure 1 New Zealand wind resource. [12]

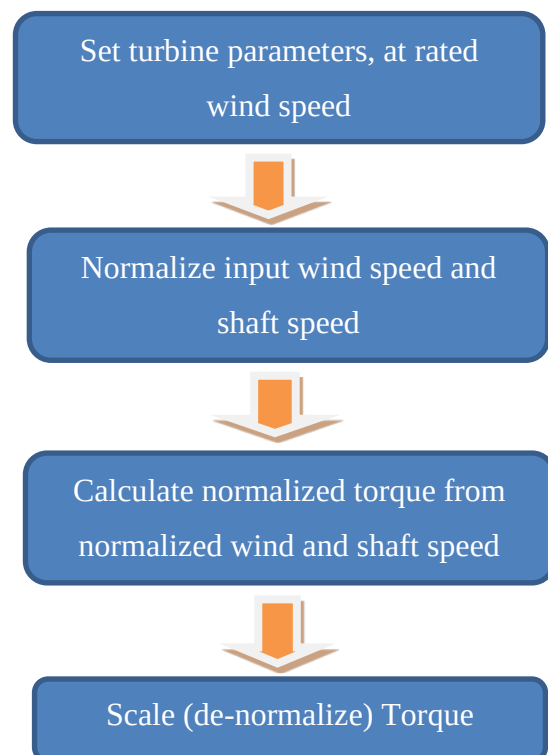


Figure 2 Wind turbine model

Table 1 Wind turbine design matrix

Turbine Model	Rotor speed	Torque	Starting Torque	Self-starting	Reliability/Durability	Efficiency	Power location
Three blade HAWT	High	Low	Low	Yes	Fair	High	Top
American wind mill	Low	High	Very High	Yes	Good	Fair	Top
VAWT	Low	Mid	Low	No	Poor	Fair	Ground

Table 2 Hydro turbine design matrix

Turbine Model	Head	Flow	Scale	Reliability/Durability
Overshot	Small	Medium to high	Pico to small	Good
Undershot	Very small	Medium to high	Pico to micro	Good
Pelton	Medium to high	Low to medium	Micro to large	Good
Turgo	Small to high	Low to medium	Pico to large	Good
Crossflow	Small to medium	High	Micro to medium	Good

Prior to running the wind turbine model in the main combiner model, it was tested on its own to verify its accuracy. In figure 3, the wind turbine output is illustrated for wind speeds of 1-6 m/s.

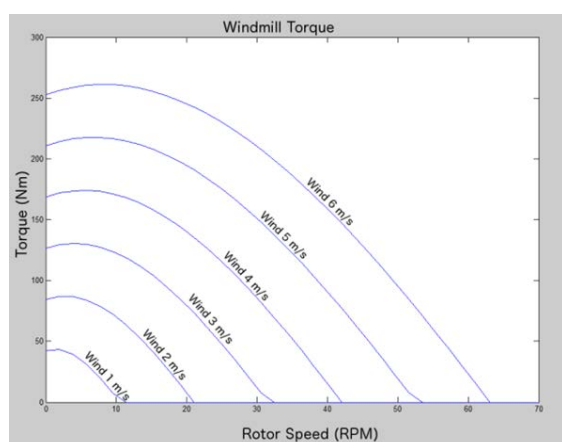


Figure 3 Wind turbine characteristics

4. Hydro Turbine Selection

Several different types of water turbines and wheels were considered, see table 2 for a comparison between these turbines. The specified pressure head of 5 meters ruled out undershot and crossflow, and made overshot undesirable because of the physical size. Therefore, Turgo type of turbine as shown in Figure 4 was thought to be suitable. Turgos have the advantage of being self-cleaning, due to non-recirculating water flow inside the turbine housing. The water jet enters the turbine runner from above and exits below, so the used water does not interfere with the incoming jet. They are Tasy to construct, and relatively cheap. Another significant factor in the choice of water turbine was the availability of mathematical model of the turbine that could be implemented in

MTALAB and incorporated into main combination model. Large scale models for both Pelton and Turgo were available however they did not scale well to the very small scale that this project is studying. The discovery of a small scale Turgo model was a contributing factor in the decision. The model used was an implementation of a model found in [14] with the findings validated experimentally, and the described model calculates turgo speed/torque characteristics from first principles, using conservation of momentum. This model can be broken into process flow as shown in Figure 5.

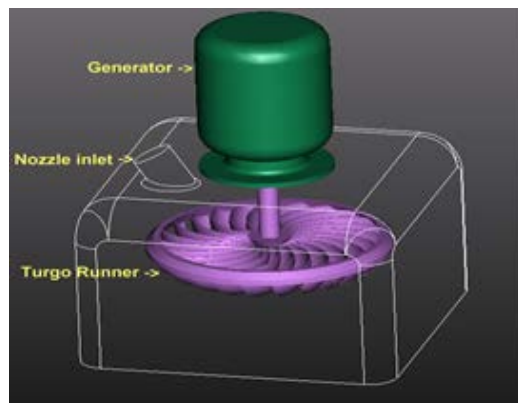


Figure 4 Turgo Turbine

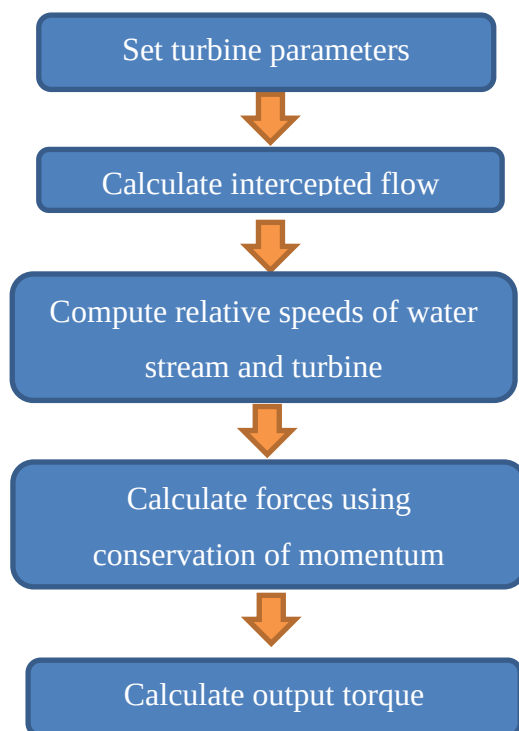


Figure 4 Turgo model

The turbine parameters are particularly important to this model because it calculates from first principles.

5 Method of Coupling

The method of coupling both the renewable energy sources is the most significant part of this work. The possibilities are as follows:

- i) Electrical combining
- ii) Mechanical
 - (a) Constant torque (“speed-split”)
 - (b) Constant speed (“torque-split”)
- iii) Electromechanical

5.1 Discussion

Electrical combination as shown in Figure 6 is the current norm. In this method, a wind turbine is installed separately to the hydro turbine, using separate electrical generators, and their outputs are combined in the electrical system of the installation. The two systems are mechanically independent

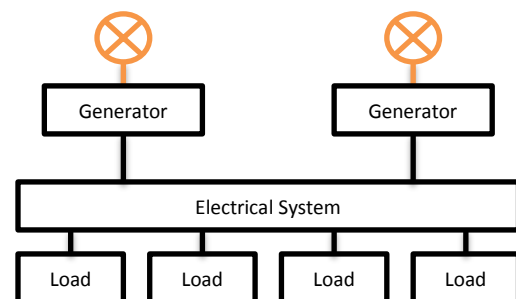


Figure 5 Conventional Electrical Combination

Electromechanical combination is a way of combining the two turbine outputs, and would involve a generator that had two rotors, instead of a rotor and stator. In this case, the two rotors would rotate in opposing directions, against each other. Because they rotate against each other and no torque is applied across the generator housing, the input torques must be equal but opposite. For reasons discussed below, this could be problematic.

If the outputs were to be combined in a purely mechanical fashion, then driving a conventional generator, two variations are

possible. These are constant torque, and constant speed. Constant torque means the two inputs must have equal torques, but the input speeds can vary with respect to each other and the frame of reference. Two methods of obtaining this were considered, using a differential gearbox, and a planetary gearbox. Both of these examples are used in the automotive industry.

A differential gearbox shown in Figure 6 will be immediately familiar to anyone with a working knowledge of automobiles, as they are universally used to supply the engine power to the wheels on either side, and provide an ability to accommodate a speed differential between the driven wheels (required when turning). While in this case the differential has a single input and two outputs, the system works fine the other way. This is evident when your car is up on jacks, and you rotate one wheel, causing the opposite wheel to turn the other way.

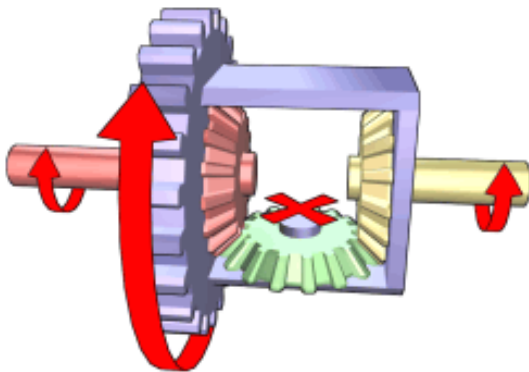


Figure 6 Differential

A planetary gearbox is commonly used in electric drills to reduce the motor speed to a usable speed for drilling, and in some aircraft to reduce the engine speed to one usable for the propeller or rotors. Toyota also uses planetary gearboxes to combine the petrol engine, two electric motor/generators, and wheels in the Toyota Hybrid System [15]. This system acts as both a continuously variable transmission for the petrol engine and electric motors, and as a way of allowing any combination of power flow between the motor/generators, petrol engine, and wheels. While this system works well in

practice, it needs high level supervisory control to coordinate the various power sources and loads, and is quite complex. The main disadvantage to a constant torque method like this is caused by the fact that the speeds of the inputs can vary with respect to each other, but the torques will be constant. If the system has inertia, which any physical system will, then the input speeds may be unstable, particularly if the speed-torque curve of a driving source is flat. This phenomenon is known as hunting, as the power sources tend to “hunt” around the operating point and never settle.

A second disadvantage is that if one source is driving the load, the other’s starting torque will be equal to the driving source (depending on relative gearing ratios, it may be different, but certainly non-zero). The system could be made to allow torque differentials also, but such arrangements generally involve friction (and thus power loss), and a complex mechanism to achieve it. Constant speed means the inputs must have the same speed in order to contribute to the output. Their torque’s add together in the output, and may vary with respect to each other. A common application of this type of drive is in multi engine helicopters as shown in Figure 7. In this case, two or more turbine engines drive the main rotor at a set speed. This arrangement makes it possible for one engine to fail, leaving the remaining operative engine(s) to continue powering the aircraft. A freewheel clutch on each input to the combining gearbox prevents the failed engine from being driven by the operative ones, which could be dangerous depending on how the engine has failed, not to mention the waste of power.

In its most basic form, this gearbox is very simple, with two input gears that both drive a single output gear. Extra reduction may be added if appropriate for the application. The main drawback to this method is that the inputs must have the same speed relative to each other. Also a free wheel clutch is required to prevent power loss to a malfunctioning or slow input. The

advantages include zero starting torque (indeed an input will not be loaded until it reaches the speed that the system is currently operating at), and perhaps most significantly the simplicity. The simpler a system, the more reliable it will be, or it will be easier to make reliable, than a complex system.



Figure 7 PT-6T Pratt & Whitney Helicopter Powerplant

Using the chosen wind turbine, the output shaft must be put through a 90-degree gearbox to pass vertically down to ground level where the hydro turbine and combining gearbox is. As it is expected that the hydro and wind turbines are offset laterally, a total of three 90 degree gearboxes are required, which can incorporate the necessary gear ratios. Figure 8 illustrates the proposed physical system design.

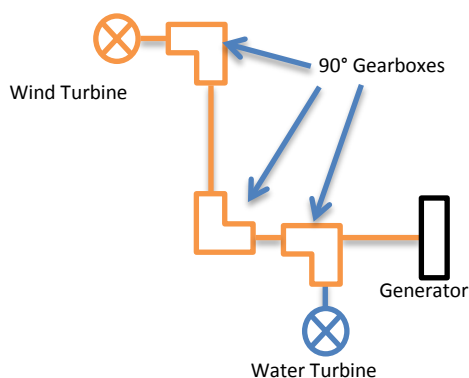


Figure 8 Physical Design

6 Generator Selection

The generator selected for this work is the venerable Fisher & Paykel Smart Drive. It is well regarded for use as a generator, after converting it from its original purpose of driving washing machines. Widely used in DIY small scale generation, they are also

used in some commercial products[16]. However research [17],[18] indicated that the common Smart Drive did not have the required power capacity for this application (peaking in the range of several hundred watts), which seeks to generate in the order of 1 kW. A test rig as shown in Figure 9 constructed by [17] coupled a small turgo turbine to a Smart Drive generator peaked at approximately 800 watts, the limiting factor being the Smart Drive. A more suitable generator (Figure 10) was found, model GL-PMG-1000 manufactured by Ginlong Technologies.

6.2 Modeling

With a rated power of 1kW, and designed for wind energy applications, it seemed a good fit for this application. The datasheet supplied by the manufacturer contained all the information needed to model the generator in Simulink. The graphs as shown in Figure 11 were plotted in an Excel spreadsheet, and a polynomial fit was applied to the points to obtain a system equation relating rotation speed to power, voltage, and torque.



Figure 9 Smart Drive and Turgo [17]



Figure 10 - 1 kw generator

Power generated was given by the equation

$$P(\omega) = -0.0032\omega^3 + 0.6836\omega^2 - 1.52769\omega \quad (2)$$

The torque applied on the shaft by the generator (of course opposing the current motion) is given by

$$T(\omega) = -0.0041\omega^2 + 0.8788\omega \quad (3)$$

The output voltage was not of concern to this project, as it is assumed that the downstream electrical systems will deal with that. Overall power generated is the important part. A MPPT (Maximum Power Point Tracking) controller may be required to maximize the output.

The generator was represented as a torque source in the simulation, taking the shaft speed as an input, and applying a torque to the system that opposed the direction of rotation.

7. Simulation Results

7.1 Windmill

To model the system the windmill had to be modeled. This proved not to be a trivial process because the torque generated by the turbine depended on both wind speed and the angular velocity of the rotor. The first model created (using the Simscape tools in the MATLAB and Simulink software packages), generated a very simple linear speed-torque characteristic. It did not take a direct wind speed input, instead using a stall torque. A rotational damper was used to make the torque reduce linearly as the rotor's angular velocity increased. In water pumping applications (where the American wind turbine is most commonly used) the starting torque is approximately 3 times that of the mean torque requirement when running [13]. This means the torque at the turbine's operating speed is one third of the starting torque.

While the simple, initial model produced a simple linear speed-torque curve, the reality is that it is a curve, albeit a fairly simple one [13]. The wind speed affects both speed



Figure 11 Generator characteristics

and torque. This is an important assumption made in the model that is created. Figure 12 shows the varying speed torque curves for different wind speeds, as modeled. The small kinks at the bottom of the 1 m/s, 3 m/s, and 5 m/s curves are an artifact of the MATLAB simulation.

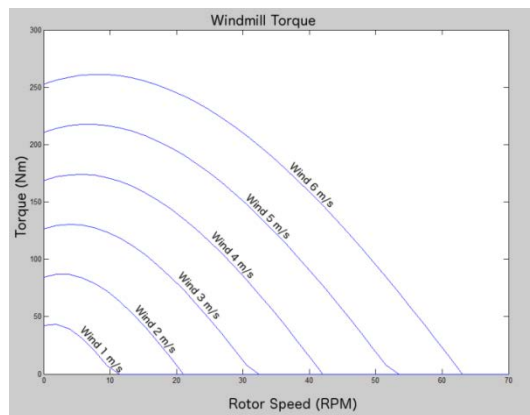


Figure 12 Wind turbine characteristics as modeled

7.2 Turgo hydro turbine

A model for a Turgo turbine in the pico-hydro scale is generated in [14]. This model was implemented in Simulink and added to the already functioning model. No work was done in attempting to optimize those parameters for this project, except for the water head, jet diameter, and turbine radius. The model does not consider windage losses inside the turbine housing. The parameters that were left as is include jet entry angle, water/turbine contact angles, and water exit angle. A 5cm jet diameter was found to produce a flow of 19.7 liters/sec when fed with 5m head water, matching the specifications of 20 liters/sec. The output of the model is illustrated in Figure 13, showing speed-torque curves for heads of 1 to 5 metres, in 1 metres increments.

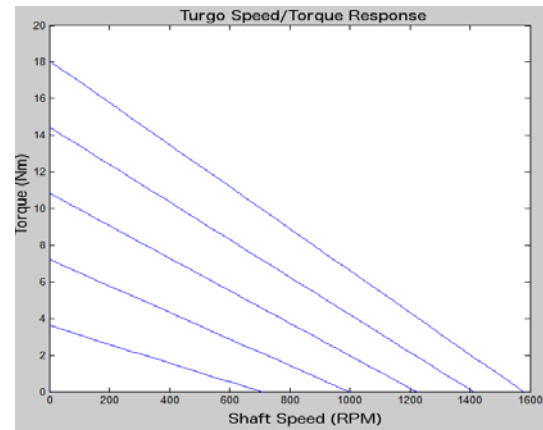


Figure 13 Turgo characteristics as modeled

7.3 Combining system

The “torque-split” combining system was modeled using the SimScape mechanical simulation toolbox, with the Simulink tool bundled with MATLAB. Only the fundamental mechanical blocks were used. The initial modeling was attempted using first principles and a complete mathematical model of the system, using only the mathematical blocks in Simulink. However, this proved very difficult to debug and improve, as every fundamental property had to be incorporated into the model. For this reason, the model was rewritten using the SimScape mechanical blocks. The wind and hydro turbines were each modeled in their own custom code blocks, and each took an input of shaft speed and generated a simulated output torque from the model contained within. Figures 14 and 15 show these custom code blocks within the main model.

The SimScape tools had common fundamental elements all ready to go, such as torque sources, inertia elements, gearboxes, sensors etc. The most significant inertia that of the wind turbine, was found to be 120kg.m², by approximating the wind turbine as a disc, a valid assumption for the solid American Wind pump.

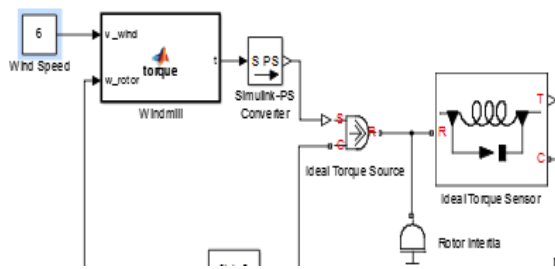


Figure 14 Wind turbine portion of main model

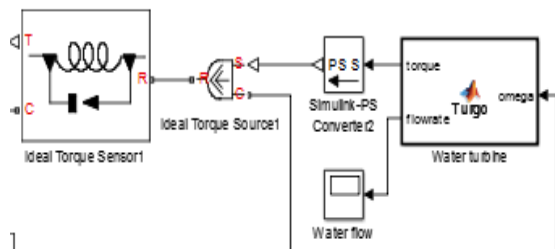


Figure 15 Generator portion, showing gearboxes

A gearbox coupled each turbine to a common shaft that drove the generator. The generator itself was implemented such that it applied a torque opposing the direction of rotation of the common shaft. This torque was determined by the speed of the shaft, using equation 3. This section of the model is shown in Figure 15. The gearbox ratios (1:12 step up for the wind turbine, 1:2 step down for the turgo) were determined by an iterative process of maximizing the power output for rated resource inputs (6 m/s wind, 20 l/s water @ 5m). In doing this, the power output was increased from 600 watts to 1040 watts.

7.3 Results

The simulation results show that the system settled at a steady state within a few seconds, after overcoming the inertias present. Figure 16 shows the power output of the generator over the first 10 seconds of operation. It settles at just below 1040 watts, using rated inputs. Figure 17 shows the power output if the wind source is removed, leaving just the hydro turbine driving the generator. Note that it is assumed a freewheel clutch effectively removes the wind turbine from the system

in such circumstances. Figure 18 shows the power output if the water turbine does not supply any power to the system, assuming a freewheel clutch is fitted on the output of the turgo turbine. The power output settles at 380 watts. This is of interest because it shows that the turbines, when driving together, can operate in a more efficient region, hence the generator is able to produce more power when both are driving together, than the sum of each turbine driving on its own.

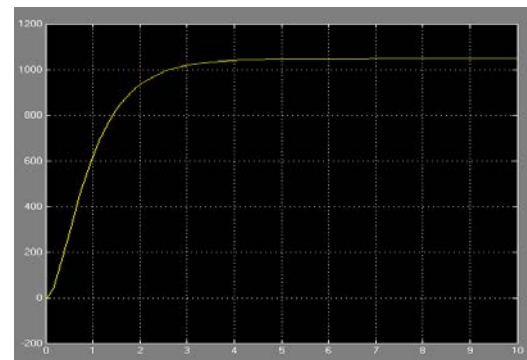


Figure 16 Power output over 10 seconds

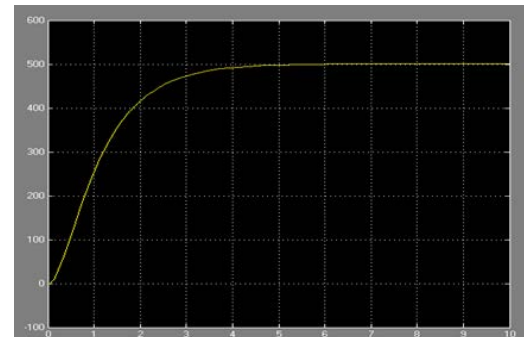


Figure 17 Power output with no wind



Figure 18 Power output using only wind, over first 10 seconds

8 Analysis of findings (Power Output)

Renewable energy sources are intermittent, especially wind and solar. This means that the system as designed will not produce its rated power continuously, but somewhat less. The average power output, long term, can be deduced by taking capacity factors into account for both the hydro and wind power sources. Conservative values for these were taken as 0.25 for the wind, and 0.9 for the hydro. In practice, it is expected that the actual values for this are more like 0.35 and 0.99, for a reliable, well designed, maintained, and situated system. Taking such conservative values allows for a simpler estimation to be done, using simple probability to calculate the long-term output.

Table 3 Output Power Calculations

Power Source	Net Probability	Net Power	Net Power
Wind + Hydro	0.9×0.25	0.225×1040	234
Wind	0.1×0.25	0.025×380	9.5
Hydro	0.9×0.75	0.675×500	337.5
None	0.1×0.75	0.075×0	0
		Average Power	581 Watts

The average power output calculated in Table 3 translates to an annual generation capacity of over 5000 kWh. While less than the average usage, energy efficient houses and practices can allow a house to get by on this much power without sacrificing very much. Of course, if combined with a grid-tie system, this is hardly a problem because power can simply be imported from the national grid as required.

9 Conclusions

This work is an attempt to make renewable energy more reliable, cost effective, and accessible by exploring a different energy

combination system to that currently applied to wind and hydro power. Instead of the usual electrical combination of wind and hydro generators this work involved combining water and wind turbines mechanically, before driving an electrical generator. This new combination system is modeled and optimized in MATLAB, using a direct combination system commonly found in multi-engine helicopters. The system is found to operate satisfactorily. The research illustrates that there is potential for further research in the areas of pump-hydro storage and using a water pump as a turbine, both as an extension of this project. Research was undertaken regarding wind and water resource availability, and the turbines were chosen with these taken into consideration. Various combination systems were explored, including torque and speed split mechanical combinations, conventional electrical combination, and using a modified switched reluctance generator as a method of electro-mechanical combination. The system met the requirements in terms of resource constraints and power output. The new combination method was modeled in MATLAB, taking advantage of previous work done on Turgo modeling and the results obtained are highly encouraging to conduct the further research in the area.

10. Future Work

The system as implemented in the MATLAB model is more complex and costly than current, simple electrical combination systems, however further research and modeling will be undertaken in regards to using a pump-as-turbine, and incorporating pumped hydro energy storage into the simulation. Furthermore, CAD modeling and computer simulation will be carried out to further optimize the model parameters. A further development to make the system more accessible and reduce cost is the possibility of using a standard water pump in place of the turgo turbine.

Computer models for such implementations are few and far between, so finding or designing such a model would be of great contribution in the area.

References

- [1] F. Spertino, A. Ciocia, V. Cocina, and P. Di Leo. (2016), "Renewable Sources with Storage for Cost-Effective Solutions to Supply Commercial Loads," in *Proc. Power Electron. Electr. Drives Autom. Motion Sympo.*, pp. 242–247.
- [2] D. Saheb-koussa, M. Koussa, S. Bellarbi, and A. Boufertella. (2016), "Fuzzy Logic Management Supervisor for Wind-Diesel-Battery Hybrid Energy System," in *Proc. Renew. Energy Congr.*, pp. 1–6.
- [3] T. Zhou and B. François. (2011), "Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration," *IEEE Transactions Ind. Electronics*, vol. 58, no. 1, pp. 95–104.
- [4] R. Huang, S. H. Low, U. Topcu, K. M. Chandy, and C. R. Clarke. (2011), "Optimal Design of Hybrid Energy System with PV / Wind Turbine / Storage : A Case Study," *Proc. IEEE Smart Grid Commun. conf.*, no. 1, pp. 511–516.
- [5] M. Santarelli, M. Cali, and Sara Macagno. (2004), "Design and analysis of stand-alone hydrogen energy systems with different renewable sources," *J. Hydrogen Energy*, vol. 29, no. 15, pp. 1571–1586.
- [6] M. K. Deshmukh and S. S. Deshmukh. (2008), "Modeling of hybrid renewable energy systems," *J. Renew. Sustain. Energy Rev.*, vol. 12, no. 1, pp. 235–249.
- [7] D. Tomislav, X. Lu, J. C. Vasquez, and M. Josep. (2016), "DC Microgrids – Part II: A Review of Power Architectures, Applications and Standardization Issues," *IEEE Transactions Power Electron.*, vol. 31, no. 5, pp. 3528–3549.
- [8] M. C. Mira, Z. Zhang, A. Knott, and M. A. E. Andersen. (2016), "Analysis, Design, Modelling and Control of an Interleaved-Boost-Full-Bridge Three-Port Converter for Hybrid Renewable Energy Systems," *IEEE Trans. Power Electron.* DOI 10.1109/TPEL.2016.2549015,
- [9] S. Moury, J. Lam, V. Srivastava, and R. Church. (2016), "A novel multi-input converter using soft-switched single-switch input modules with integrated power factor correction capability for hybrid renewable energy systems," in *Proc. IEEE Appl. Power Elect. Conf. Expo.*, pp. 786–793.
- [10] W. Jiang and B. Fahimi, "Multi-port Power Electric Interface for Renewable Energy Sources. (2009)," in *Pro. IEEE Appl. power Electron. conf.*, pp. 347–352.
- [11] Z. Rehman, I. Al-Bahadly, and S. Mukhopadhyay. (2015), "Dual input-Dual output Single Inductor DC - DC Converter for Renewable Energy Applications," *IEEE 4th Int. Conf. Renew. Energy Res. Appl.*, pp. 783–788.
- [12] NIWA. (n.d.). Wind Energy Map. Retrieved August 9, 2015, from http://www.niwa.co.nz/default/files/imported/__data/assets/image/0004/50539/renewable3_large..
- [13] P. Fraenkel, R. Barlow, Crick, F. A. Derrick, & V. Bokalders, (1993). Windpumps, A guide for development workers. Nottingham, UK: Intermediate Technology Publications Ltd.
- [14] S. J. Williamson, B. H. Stark, and J. D. Booker. (2013), "Performance of a low-head pico-hydro Turgo turbine," *J. Appl. Energy*, vol. 102, pp. 1114–1126.
- [15] J. M. Miller. (2006), "Hybrid electric vehicle propulsion system architectures of the e-CVT type," *IEEE Trans. Power Electron.*, vol. 21, no. 3, pp.

756–767.

[16] B. Leyland,(n.d.) “From washing machine motor to micro hydro generator,” Retrieved March 22, 2015 from www.bryanleyland.co.nz/uploads/2/9/7/1/29710909/smartdrivemicrohydro.pdf

[17] Chalko, T. (2005). “Optimizing a Permanent Magnet Alternator for micro-hydro application,” Retrieved March 22, 2015, from http://mtbest.net/SD_modification.pdf.

[18] J Thwaites. (n.d.). “Fisher and Paykel washing machine motors for electricity generation,” Retrieved August 10, 2015, from http://www.sustainability.ofm.uwa.edu.au/__data/page/83884/FP.pdf.