A Low-Power Floating-Turbine Generation System for Small Rural Communities

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Abstract

The use of a floating turbine, a low-power hydraulic turbine which transforms the kinetic energy of water into mechanical energy using the same principles as those for producing wind power, can potentially help to produce electrical energy in some areas near rivers. This paper addresses the relation between the wind and floating turbines, presents a theoretical analysis of a floating turbine power generation system, shows the system simulation in Matlab^{TM}*/simulink environment and illustrates the feasibilities of the proposed ideas by presenting experimental results on a scaled-down prototype.*

Keywords*: Floating turbine, rectifier, DC/DC converter, permanent magnet synchronous generator (PMSG), and inverter.*

1. Introduction

The world is faced with the serious problem of producing energy to support, and in some cases, to improve the standard of living of human beings [1], [2]. Some facts on this will be expounded on this paper.

First, disproportional energy consumption has been remarkable in the industrial countries. For these countries, all forms of conventional energy supply (fossil fuel) have been exploited. Unfortunately, some sources of energy present some secondary effects to the environment. For instance, fossil fuels irreparably damage the environment by emitting gases like CO2 [3]. Uranium produces significant amount of radiation; therefore, nuclear power plants need sophisticated technology to overcome the radiation propagation problem [4]. Apart from the previously mentioned problem, the world is running out of uranium and fuels. Noticing this essential problem, these countries have started to introduce new technologies by integrating renewable energy sources into their fuel mix.

Second, energy supply is still at an elementary stage in most developing countries since they are still introducing efficient conventional energy supplies. For this reason, many citizens in these countries do not have access to an abundant, secure, clean, affordable, and sustainable energy supply.

Especially, many people do not have access to electricity. To elucidate very well the problem, people who are facing this problem are those who are living in rural areas. This problem is most remarkable in Africa, in some Asian countries and in some Latin American countries [3].

Anybody can ask if these countries have to go the long way the industrial countries went through to establish an efficient energy supply chain, or if the developing countries must start to introduce renewable energy sources as well since they are also available in these countries. For instance, the solar and wind energy sources can be exploited. Moreover, in some countries there are several rivers which can be exploited in different ways to generate electricity. One way can be conventional hydropower plant and another one can be the application of the wind energy principles to floating turbines in rivers. Therefore, this paper promotes the use of “A Low –Power Floating Turbine Generation System for Small Rural Communities”. The case study emphasizes on the African country of Rwanda. The next section deals with a small-scale power generation system using the river current.

2. Small-Scale Power Generation Using the River Current

The river kinetic energy may be converted into mechanical energy using floating turbines. Any river with a speed greater or equal to 0.5 mps, and at least 1.5 m of depth can be used to generate electrical energy using floating turbines [5]. The floating turbine can be classified as a small-scale generation system.

The average power rating of a single floating turbine is normally between 0.5 and 5 kW [5]. The use of a floating turbine can potentially help some areas nearby rivers to produce electrical energy yielding an improvement in the quality of life.

Many rivers in several African countries meet these requirements. For example, my beloved Rwanda, one of the African countries sharing the Nile river basin, hosts some rivers which can be used to exploit the floating turbine.

The floating turbine can be used to supply electricity villages nearby Ruvubu, Nyabarongo and Akagera rivers and some other rivers. The floating turbine, a small-scale power generation system, is not harmful to the environment as classical hydropower plants [5]. In other words, the construction of a dam is not needed for the floating turbine whereas the dam required in the classical hydropower plant that destroys the ecosystem, not only affecting humans but also wildlife.

Fig. 1 addresses the floating-turbine generation system block diagram. The block diagram is composed with a PMSG, rectifier, DC/DC boost converter, inverter and a load. Different reasons are based on to choose the components of the block diagram. First, the choice of PMSG as a generator of the system is based on its good efficiency; the excitation is provided by permanent magnets [6], [7]. Moreover, it has a high power density; the machine is small and light weight. Furthermore, its control is relatively simple when applied to the case of the floating turbine.

The river speed changes randomly having an effect on the output voltage of any generator coupled to the floating turbine. Thus, the PMSG output voltage will be varying based on the floating-turbine torque. In this case, a power electronic interface is needed to output a constant voltage to the electric load. Several power electronic topologies can be employed depending on the load and generator characteristics. The power electronic topology presented on Fig. 1 is simple and easily controllable. The next section of this paper presents a mathematical model of the floating turbine. The model is used to simulate the turbine in Matlab^{TM} /simulink.

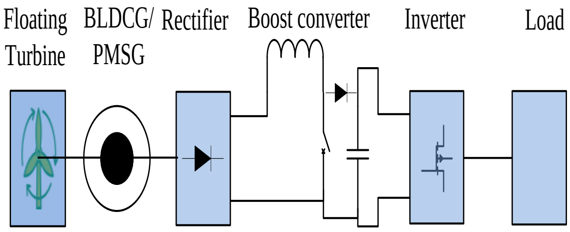

Fig. 1 Floating-Turbine Generation System Block Diagram

3. Mathematical Model of the Floating Turbine

Consider a river running a long straight path (i.e., along x-axis) with initial velocity $\vec{V} = v_{x'o}.\hat{i}$ and final velocity $\vec{V} = v_{x'f}.\hat{i}$. The mechanical work is then calculated as:

$$W = \int_{x_o}^{x_f} F_x dx = \int_{x_o}^{x_f} m \frac{dv}{dt} dx = \int_{v_o}^{v_f} m v_x dv_x \qquad (1)$$

with $F_x = m\frac{dv_x}{dt}$, m is the mass of the river, and $v_x = \frac{dx}{dt}$ the speed. Then,

$$W = \int_{v_o}^{v_f} m v_x dv_x = \frac{1}{2} m v_{x_f}^2 - \frac{1}{2} m v_{x_o}^2 = \Delta E \qquad (2)$$

where E is the kinetic energy [7].

By integrating the kinetic energy the mechanical power is given by the following expression:

$$P = \frac{d}{dt}\left(\frac{1}{2} m v_{x_f}^2\right) = \frac{1}{2}(2 m v_{x_f} \frac{dv}{dt} + v_{x_f}^2 \frac{dm}{dt}) = \frac{1}{2}\dot{m} v_{x_f}^2 \qquad (3)$$

With v_{xf} =constant, $\dot{m} = \rho s v$, and are respectively the density of water and the water swept area.

Eq. (3) becomes:

$$P = \frac{1}{2}\rho s v_{x_f}^3 = \frac{1}{2}\rho \frac{\pi D}{4} v^3 \qquad (4)$$

where D is the floating turbine diameter, and *v* the river speed.

Practically, the floating-turbine must have performance coefficient, Cp, is as a function of the tip ratio, $\lambda = r\omega / v$, and the pitch angle of the floating turbine β, with ω the angular speed of the floating turbine, v the river speed and r blade radius [8]. The fact is that the floating turbine is coupled to the electrical generator so that the upstream water speed, a linear speed, is transformed into an angular speed.

The mathematical model of the floating turbine is similar to the one of the wind turbine even though there are not many assumptions to be done for the floating turbine as for the wind turbine. The main difference refers to wind gusts whereas the river speed could be considered quasi constant.

Nevertheless, the target for both turbines is to calculate the mechanical power by applying the average linear speed. For the wind turbine, there are many models which have been employed to get the average wind speed. For instance, the Weibull distribution can be used to calculate the turbine power [9] and the average river speed through the floating turbine can be calculated from the Betz's limit theory [8].

Basic conservation laws can be used to explain the common characteristics between the water and wind turbines; all incompressible fluids have the same conservation of mass and momentum theories. Some turbulence models show the relation between air and water.

Experimental work showed that the default values of the water and air "standard k-ε model" constants are similar during homogeneous and turbulent states [9]. For this reason, the floating and wind turbines have the same mechanical characteristics. Since it is known that the floating turbine acts like a wind turbine, its mathematical model is similar to the one of the wind turbine [5]. Thus, the Cp, a function of the tip ratio and the pitch angle, plays a big role in the floating-turbine modeling [10], [11].

Even though different numerical methods have been used to estimate Cp, all of them give the same Cp approximation; the one in reference [10] is employed for this paper:

$$C_p(\lambda,\beta)=c_1\left(\frac{c_2}{\lambda_i}-c_3\beta-c_4\right)e^{\frac{-c_5}{\lambda_i}}+c_6\lambda \qquad (5)$$

Coefficients c_1, c_2, c_3, c_4, c_5, and c_6 are defined in [11]. The λi is function of β and λ parameters:

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.0035}{\beta^3+1} \qquad (6)$$

Fig. 2 shows the Matlab^{TM} simulation block diagram of the *Cp* with the pitch angle equals to zero, and the characteristic of it is shown in Fig. 3. The floating turbine operates at the maximum value when the Cp value is around 0.47. Now that the maximum *Cp* is known, the maximum power as well as the torque produced by the floating turbine can be easily calculated:

$$P_{opt}=\frac{1}{2}\rho C_{p(opt)}\pi\frac{r^3\omega^3}{\lambda_{(opt)}^3} \qquad (7)$$

$$T_{(opt)}=\frac{1}{2}\rho s\frac{c_{p(opt)}}{\omega}v^3 \qquad (8)$$

The P_{opt} is the optimum power which corresponds to the maximum *Cp* as function of the optimal tip ratio, $\lambda_{(opt)}$. The floating-turbine torque depends on the generator speed, $\omega_g=k*\omega$[8], *k* is the ratio between the floating turbine and generator speed. Eq. (8) can be used to simulate the floating turbine. Fig. 3 presents the floating turbine block diagram in Matlab^{TM}/ Simulink. The floating turbine will use the same block diagram as the one for the wind turbine available in Matlab/simulinkTM [12]; the difference will be the density value used for the fluid. The floating-turbine mechanical torque will be calculated by using a water density of 1000kg/m3, whereas the wind turbine mechanical torque uses the air density, 1.29kg/m3.

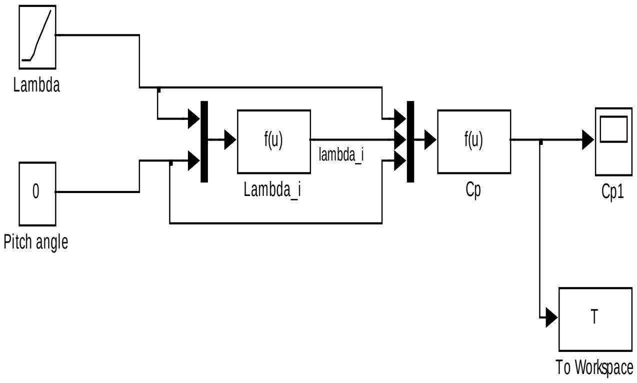

Fig. 2 C_p Matlab/Simulink Block Diagram

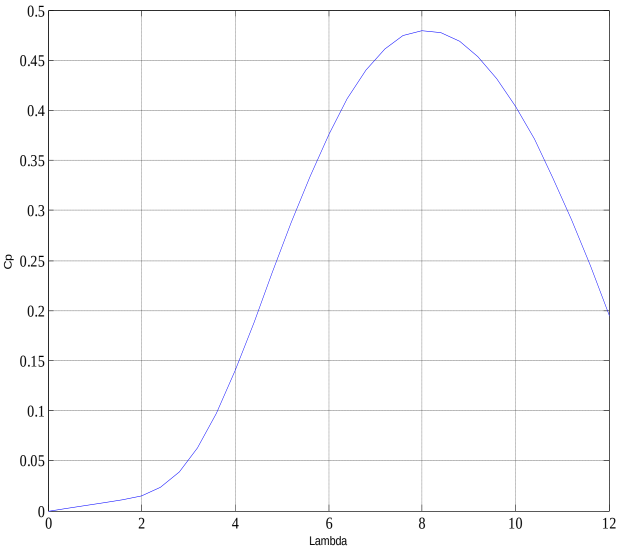

Fig. 3 Floating Turbine *Cp* Curve

The difference is that the nominal and exploitable wind speed varies from 6 m/s to 15.5 m/s whereas the river speed goes from 0.5 m/s to 4 m/s. Therefore, the floating-turbine simulation set up used the average speed of 2 m/s in this research [5]. Pitch angle, river and generator speeds are inputs and the mechanical torque is the output. To maximize the floating-torque value, the pitch angle is zero, the generator speed is 1800 rpm, and the water swept area is 1.766 m^2 (the blade radius is 0.75 m). The calculated nominal mechanical output power of the floating turbine is approximately 3 kW. The generator electrical power is approximately 2.5 kW; this means that the electrical torque is 12 Nm. The gear box with train ratio of ¼ is necessary to drive the generator. During this simulation, the gear box is considered as a constant gain.

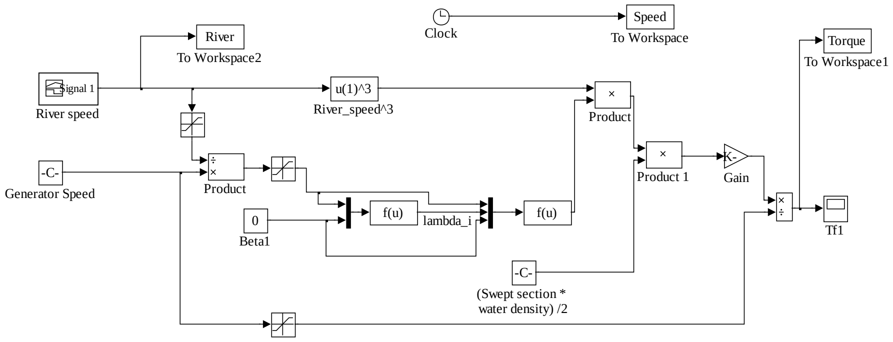

Fig. 4 Floating-Turbine Simulation Block Diagram

Fig. 4 shows the floating-turbine simulation block diagram that computes the torque using Eq. (8) in order to meet the generator torque value. The torque characteristics are influenced significantly by Cp; this phenomenon is obvious for the wind turbine [8].

Fig. 5 illustrates the floating-turbine torque characteristics as a function of river speed. The torque behavior has a strong impact on the whole system; in other words, the performances of the power electronic systems and generator depend strongly on the floating-turbine torque characteristics.

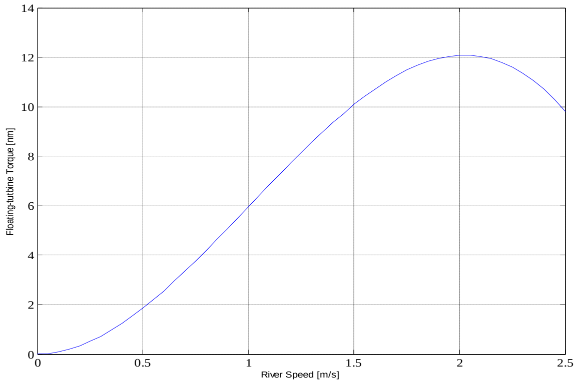

Fig. 5 Floating-turbine Torque Characteristics versus River Speed

4. The floating Turbine System Simulation

The simulation shows the feasibility of “A Low –Power Floating Turbine Generation System for Small Rural Communities”. Different techniques found in [13], [14], and [15] were used to size the rectifier, the DC/DC boost converter, the inverter and the filter. This paper chooses to use PI control at level of the dc link because it is simple and easy. Table I. presents different values used in the simulation. The simulation is presented on Fig. 6.

Table 1. Floating Turbine Specifications

Load	
Resistance [Ω]	10
Power [W]	242
Transformer	
Power* [W]	500
Voltage on Secondary Side [Vrms]	110
Efficiency*	90%
Turns Ratio	3.14
Single Phase Inverter (PWM Unipolar Switching)	
Input Voltage [Vdc]	53
Output Voltage [V rms]	35
Modulation Index	0.9
Switching Frequency	
Boost Converter	
Minimum Input Voltage [V]	22.5
Maximum Input Voltage [V]	53
Output Voltage [V]	53
Nominal Duty Cycle	0.5
Maximum Duty Cycle	0.6
ki	8
kp	0.003
Rectifier	
Maximum Input Voltage [V]	39.26
Minimum Input Voltage [V]	16.67
Output Voltage [V]	$22.5 \leq$ Voltage ≤ 26.5
Efficiency	94%
PMSG	
Voltage [V]	18
Speed [rpm]	850
Power [W]	300

* Estimated values

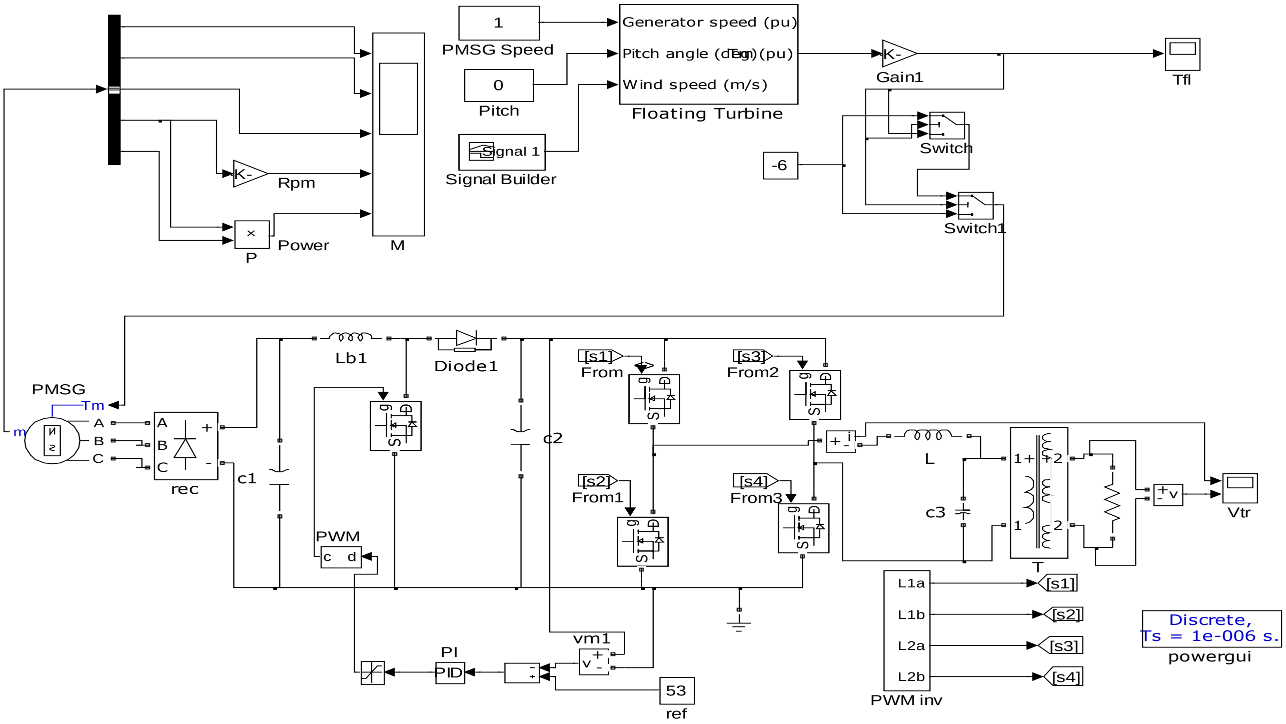

Fig. 6 Schematic of the Floating-Turbine Power Generation System

Fig. 7 shows that the voltage varies between 0 and 50 V (peak) for one half-period and from 0 to -50 V (peak) for the other half period before the output LC filter and transformer. The current varies in a similar way from about 5 A to – 5A (i.e., resistance load).

On the other hand, the voltage varies between -150 V to 150 V (peak to peak) and the current changes from - 15 A to 15 A (peak to peak) when adding the LC filter and transformer. This case has a larger current because the equivalent resistance on the transformer high voltage side is 4 Ω instead of 10 Ω as in the first case without transformer.

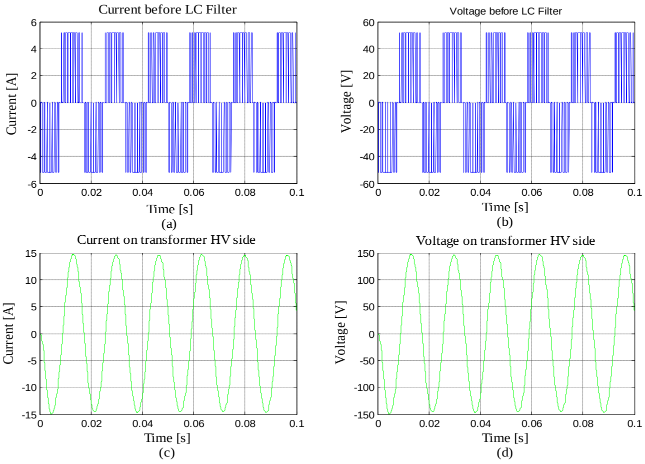

Fig. 7 Inverter Current and Voltage Waveforms after adding Filter and Transformer

In order to not exceed the rated calculated power, the cases of high currents must be avoided during the experimental work.

5. Small-Scale Floating-Turbine Power Generation Experimental Results

Fig. 8 shows the main components of lab experimental step up of the floating-turbine power generation system. In this step up, the floating turbine is emulated by the IM based on the mathematical model given in the third part of this paper. The Baldor inverter drives the floating-turbine referred on a torque signal measured by the torque sensor via the I/O control desk.

The Baldor inverter is interfaced to the I/O control desk by dSPACE unit and the host computer. The voltage generated by the PMSG is applied to the three-phase diode rectifier which was realized by using the three phase-phase IGBT module (PM75CSA120 [16]). Rectified voltage is applied to the boost converter which receives a PWM signal, switching signal, from the host computer via the I/O control desk. The output of the boost converter supplies an electrolytic capacitor; the dc link applied to the single-phase inverter. Fig. 8 illustrates the voltage at the primary side (purple) and at secondary side (blue) of the transformer. On the same figure, the red line shows the FFT (Fast Fourier Transform). The inverter output voltage is 31 V (rms) instead of 35 V (rms). The transformer output voltage is 97 V (rms) instead of 110 V (rms).

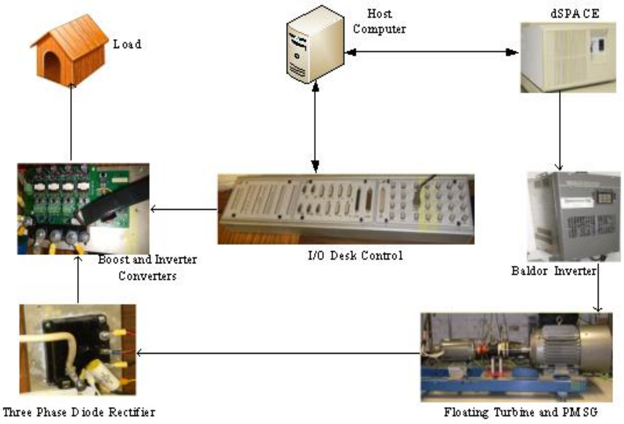

Fig. 8 Principal Subsystems of the Floating-Turbine Power Generation Experimental Set up

This difference is due to that fact that during the simulation the inverter modulation index was one whereas the inverter modulation index during the lab experiment was 0.95, a practical modulation index. The LC filter inductance was increased to 9 mH to improve filtering of the harmonics. Fig. 9 shows the results, the red line is the FFT and the green curve is the transformer output voltage. For the previous case, the third harmonic is significant but after increasing the inductor value, the first significant harmonic after the fundamental is the fifth harmonic.

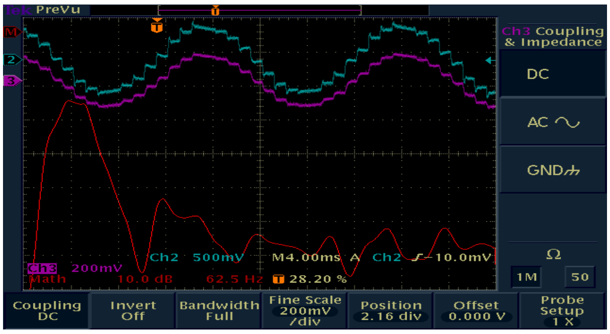

Fig. 9 Floating Turbine Power Generation Experimental Results with 34 μH Filter Inductor

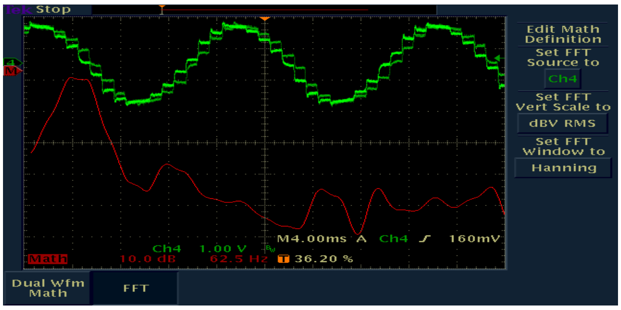

Fig. 9 Floating Turbine Power Generation Experimental Results with 9 mH Filter Inductor

6. Conclusion

To conclude, this power generation system requires several power electronic subsystems; the rectifier, boost converter, and inverter. All these systems have to be reliable and rugged so the floating-turbine power generation system can be used by individuals with no formal training in electrical systems. This system may not be cost effective for applications in developing countries. It can be used for domestic electrical loads and farming. The filter of the system must be well designed in order to get pure sinusoidal wave forms.

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