Frequency Measurement using Magnetostrictive Amorphous Wire (MAW) Sensor and Investigation of Electrical Parameter Variations on a Micro Hydro Power Plant (MHPP) under Various Consumer Load Conditions

R. A. Ofosu, J. N. Nderu, K. K. Kaberere, S. I. Kamau, A. M. Muhia

Abstract—This paper presents frequency measurement of Micro Hydro Power Plant (MHPP) generator using Magnetostrictive Amorphous Wire (MAW) sensor and investigation of the variations of various electrical parameters under various consumer loads. The purpose of the study is to determine how the electrical parameters such as frequency, power, current and voltage of a balanced 3-phase synchronous generator for a MHPP varies under a purely resistive balanced load. In essence, the operation of the frequency sensor is based on Large Barkhausen Jump (LBJ) which refers to the sudden reversal or change of magnetization when the magnetic flux reverses. Due to LBJ, MAW generates very sharp and stable voltage spikes which are induced in a pickup coil wound around the MAW. The frequency measured is basically the number of voltage spikes recorded per second. The other parameters are measured with a 3-phase meter. It is observed that as the consumer load decreases in a typical MHPP, there is a corresponding increase in frequency and voltage, and a decrease in current as the power factor remains unity for a purely resistive balanced 3-phase loads. The results from this study clearly show the necessity of an Electronic Load Controller (ELC) to divert excess load to a damper load when the consumer load varies in a MHPP. This will avert the problems encountered in a MHPP such as damaging of the generator due to overheating of the windings and dimming of light due to frequency variation which directly affects the system voltage and current and the consequent damage to electrical appliances connected to the load.

Keywords—Magnetostrictive Amorphous Wire Sensor, Micro Hydro Power Plant, Microcontroller, Synchronous generator.

I. INTRODUCTION

IN recent years there has been a continuous improvement of power generation from renewable energy sources such as micro hydro in developing countries due to the volatile oil prices, developments at a faster rate and the need to reduce the emission of greenhouse gases.

Micro hydro is the small scale harnessing of energy from falling water such as steeped mountain rivers generating typically less than 100 kW using the run-off-river type flow of water hence it does not require the construction of expensive dams when compared to large hydro plants. It is categorized among the various schemes of hydro power generation as shown in Table I. Micro hydro power is one of the most economical and renewable source of energy supplements to off grid areas in rural communities.

TABLE I
HYDRO POWER SCHEMES AND THEIR GENERATING CAPACITIES [1]

Type	Capacity
Large-hydro	More than 100 MW and usually feeding into a large electricity grid
Medium-hydro	15-100 MW- usually feeding a grid
Small-hydro	1-15 MW-usually feeding into a grid
Mini-hydro	Above 100 kW, but below 1 MW; either stand-alone schemes or more often feeding into the grid
Micro-hydro	From 5 kW up to 100 kW; usually provided power for a small community or rural industry in remote areas away from the grid
Pico-hydro	From a few hundred Watts up to 5 kW

In principle, the working of the Micro Hydro Power Plant (MHPP) is similar to that of the large hydro plant. Hydro power is driven by extracting the potential energy from water over a height difference. The energy of the moving water is converted into mechanical energy by rotating a turbine, and which is then converted to electrical energy by means of a generator coupled to the turbine [2].

Various frequency sensing transducers have been designed by researchers [3], [4], [5] to measure the frequency of MHPP. Relays, tachogenerators and digital shaft encoders are normally used as frequency sensors

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which are unreliable and are very expensive [6]. However, recent trends in technology have shown that Magnetostrictive Amorphous Wire (MAW) sensor can be accurately and efficiently used to measure the frequency and has numerous advantages when compared to the conventional frequency measuring devices [4], [5].

This paper therefore seeks to measure the frequency of a MHPP using MAW sensor, and to determine how the electrical parameters such as frequency, power, current, and voltage of a balanced 3-phase synchronous generator for a MHPP varies under a purely balanced resistive load. The results from this work will immensely help in the design of Electronic Load Controller (ELC) to keep the frequency of the MHPP constant under varying consumer loads.

A. Principle of Frequency Sensing using MAW

MAW is prepared by rapid quenching in rotating water. The molten alloy cools rapidly to bypass crystallization phase resulting in a wire shaped amorphous solid [3]. The sensor is MAW with the composition $(Fe_{50}Co_{50})_{78}Si_7B_{15}$ and 125 μm diameter, placed in a pick-up coil of 3000 turns.

In principle, the sensor is based on LBJ which refers to the sudden reversal or change of magnetization when the magnetic flux reverses. Due to LBJ, MAW generate very sharp and stable voltage spikes when the magnetic field reverses.

In operation, permanent magnets are firmly attached to the shaft of the rotor in order that they are not displaced off to avoid causing any injuries. When a permanent magnet with unlike poles facing each other is attached on the rotor shaft and a pick-up coil placed near the rotor with the amorphous wire inside the coil, as the permanent magnet rotates due to rotation of the rotor, voltage spikes are induced in the coil due to the sudden reversal in magnetic flux in the amorphous wire core [4], [5]. The setup is illustrated in Fig. 1.

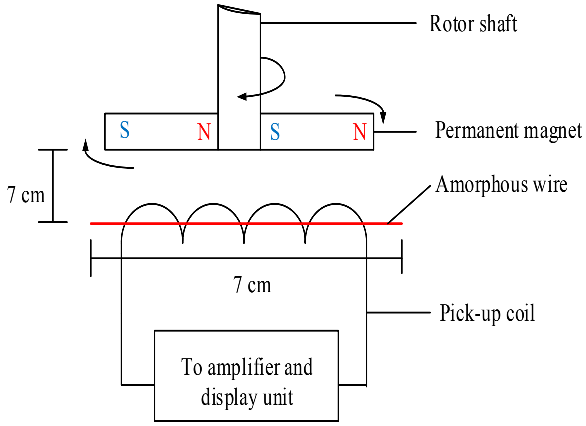

Fig. 1 Schematic diagram showing operation of the sensor

The voltage spikes are induced in the pickup coils every time the north pole of the magnet comes close to the wire. The frequency of the induced voltage spikes is therefore the number of times the north pole passes close to the wire per second, thus the speed of the rotor in revolutions per second.

From experiment, the critical length and diameter of wire, and horizontal and vertical distance at which LBJ and stable voltage pulses occurred for the MAW with the composition $(Fe_{50}Co_{50})_{78}Si_7B_{15}$ are 7 cm and 125 μm respectively. It is observed during the experiment that the signal is lost when different wire length and a critical distance other than 7 cm is used [7].

B. Amplifier and signal Conditioning Circuit

The signals obtained from the pick-up coil is a pulse of low value which is in the order of millivolts generally between 80 mV and 200 mV peak voltage. For the frequency signals generated by the wire to communicate effectively with the microcontroller, it must be amplified to improve the quality of the signal waveform and then converted into HIGH (5V) and LOW (0V) signals. This is achieved by using a two-stage inverting amplifier as shown in Fig. 2.

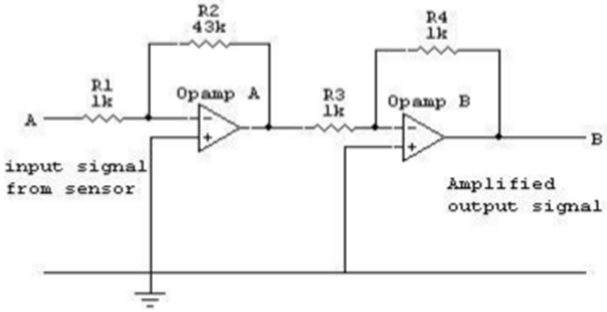

Fig. 2 Amplifier Circuit

The first stage amplifies the signal while the second stage has a gain of one which serves to invert the signal back to its initial form. The gain of the amplifier circuit is calculated as shown in (1).

$$Gain = \frac{R_2}{R_1} = 43 \tag{1}$$

The MAW generates both positive and negative voltage spikes which cannot be interfaced with the Arduino microcontroller which only operates with a LOW or HIGH (0V or 5V) signals. There is, therefore the need to remove the negative voltage spikes for easy communication with the microcontroller. The TTL circuit shown in Fig. 3 is used for this purpose.

When a positive voltage spike appears at the base of the npn transistor, the base is biased which causes current to flow from positive to ground. Since almost all the drop is across Resistor (R6), the input to the NOT gate is 0 hence the output is HIGH. In the same scenario, when a negative voltage spike appears at the base of the npn transistor, the base is not biased. Therefore, there is no drop in the resistor (R6). Hence the input to the NOT gate is 1 thus the output is LOW. The TTL circuit also serves to filter any noisy signals.

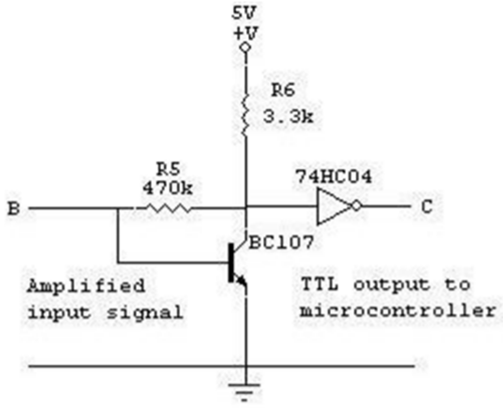

Fig.3 TTL Conversion Circuit

C. Synchronous Generator

For experimental purposes, The MHPP is a standalone 3-phase synchronous generator of the following specifications: 350 VA, 415V, 50 Hz, 2-pole, 3000 rpm.

The synchronous generator is by definition synchronous, meaning that the electrical frequency produced is locked in or synchronized with mechanical rate of rotation with the generator [8]. Synchronous generator consists of windings in the rotor (field windings) and the stator (armature windings). The rotor is rotated by a prime mover while a DC supply called the field current, I_F or excitation is applied to the field windings.

This results in a rotating magnetic field that induces a voltage on the stator windings according to Faraday’s law of electromagnetic induction. The frequency of the generated voltage is dependent on the speed of rotation of the rotor and the number of poles of the machine as given by (2).

$$F_e = \frac{n_m P}{120} \tag{2}$$

where F_e is electrical frequency (Hz), n_m is mechanical speed of magnetic field (rpm) and P is number of poles. The voltage induced in the stator windings is given by (3).

$$E_A = K\phi\omega \tag{3}$$

where, K is a machine constant, ϕ is flux and ω is the angular velocity.

D. Experimental Setup

As shown in the experimental set up in Fig. 4, DC series wound motor coupled to a 3-phase synchronous generator is used as a prime mover to drive the motor-generator set. The synchronous generator is connected in star configuration.

A DC variable power supply (0-500 V dc, 4 A) is used to power and control the speed of the DC motor which in turn rotates the 3-phase synchronous generator. A fixed DC (220 V dc, 3 A) supply with a 5 kΩ rheostat is connected in series to the synchronous generator field windings so as to increase the excitation current to attain the required terminal voltage

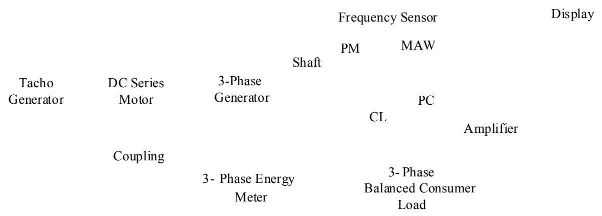

Fig. 4 Experimental Set up

DC series motor is used as a prime mover because of its torque speed characteristics, which shows that with a constant voltage source, speed reduces with increased loading. As the motor is loaded, the torque developed by it must increase. The increase in the torque necessitates an increase in the armature current since torque is directly proportional to the square of the armature current as governed by the formula in (4).

$$T = kI_a^2 \tag{4}$$

The increase in the armature current causes an increase in the voltage drop across the armature-circuit resistance, the field-winding resistance, and the external resistance. For a fixed applied voltage, the back emf must decrease with load. [9].

In operation, a 3-phase balanced rheostat each with specification 5 kΩ is connected at the output terminals of the synchronous generator as consumer load. A balanced load is used in the sense that if one phase is slightly loaded than the others, its voltage will decrease due to the drop in $R_a.I_a$ and $I_a.X_L$ in the stator winding. This drop in voltage cannot be compensated by modifying the field current because the voltage of the other phases would also increase therefore resulting in the phases been unbalanced. Hence the need for a balanced load.

The speed of the DC motor is first varied to run at 50 Hz, 3000 rpm which is the rated frequency and speed of the generator. The speed is monitored with a tachogenerator coupled to the motor shaft. The excitation current is increased to attain the required terminal voltage. The generator is then loaded by varying the balanced rheostat.

As the load on the generator is increased, the speed and thus the frequency drops. Hence the speed of the DC motor is increased to bring back the frequency and speed to 50 Hz and 3000 rpm respectively. With is arrangement, the loaded generator has the following operating parameters: 227.9 V/phase, 0.251 A, 49.92 Hz, and unity power factor.

With the excitation and speed of the generator fixed at these operating points, the rheostat is varied from full load to no load while electrical parameters such as power, voltage, current and power factor is measured with a 3-phase energy meter and recorded.

The frequency is measured with the MAW placed in a pickup coil (PC) after it has been amplified and fed to the microcontroller (μC). Atmega 328 Arduino board is used. A The permanent magnets (PM) mounted at the generator shaft separated by a critical length (CL) of 7 cm is used to increase the strength of the of the magnetic field hence the magnitude of the signals from the pickup coils. The signals are displayed on a digital oscilloscope.

II. RESULTS AND DISCUSSION

A. Results from frequency measurement

As shown in the waveform in Fig.5, the signal from the pickup coil is a low signal with a peak to peak voltage of 250 mV. The signal also has noise component which is filtered by the amplifier and the signal conditioning circuit. The frequency measured is 50.21 Hz.

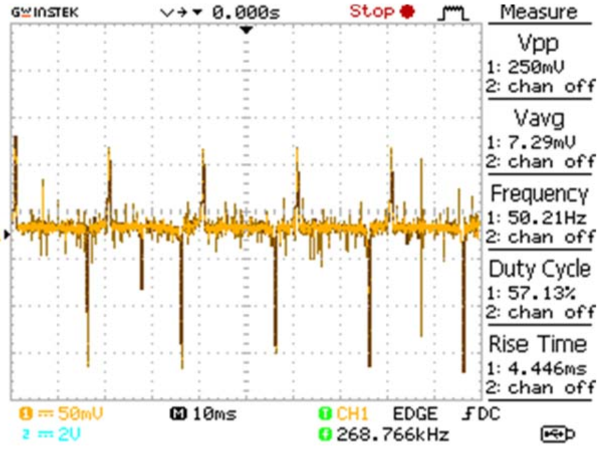

Fig. 5 Low Signals from the pickup coil

The amplified signal waveform is shown in Fig. 6 and Fig. 7 respectively. It can be seen that the signal in Fig. 6 is inverted since in the first stage of amplification, an inverting amplifier is used. Fig. 7 shows the signals in its initial form after a unity gain is applied at the second stage of amplification. The frequency recorded is 50.2 Hz which corresponds to that of the original signal. The peak to peak voltage after amplification is 10.7 V as shown in Fig 6 and Fig. 7 respectively. This is calculated as $V_{pp} = 0.25 \times 43 = 10.75\ V$.

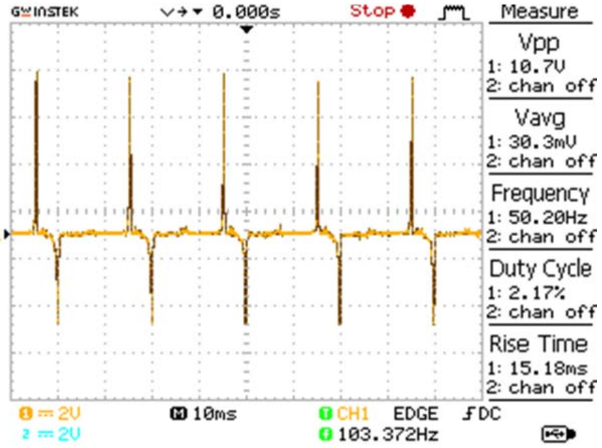

Fig.6 Amplified inverted signal

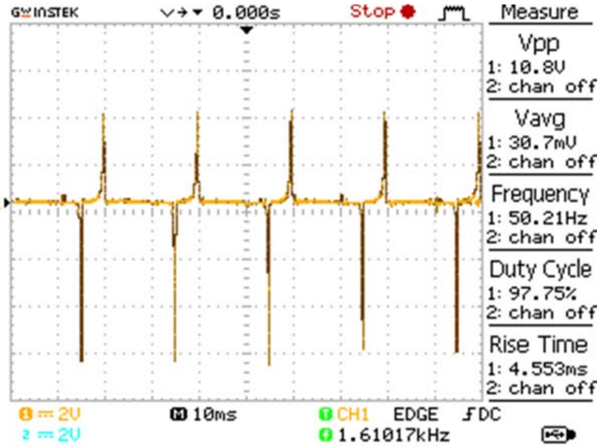

Fig. 7 Amplified signal in normal form

Fig. 8 shows the signal waveform at the output of the TTL circuit. It can be seen that the negative signal is chopped off remaining only the positive waveform which is a HIGH and LOW signals for easy communication with the Atmega 328 microcontroller. The peak to peak voltage after TTL is 4.44 V.

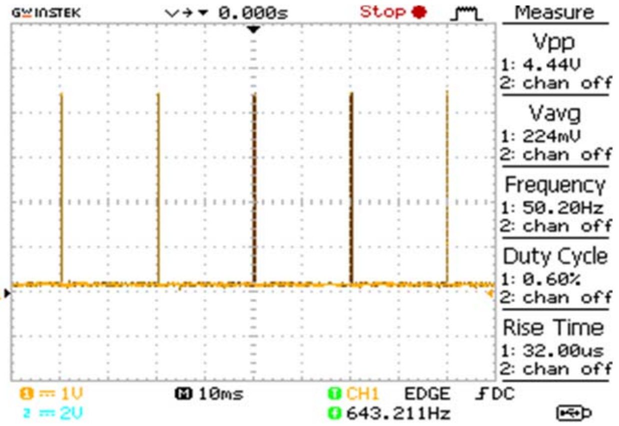

Fig. 8 TTL output waveform

B. Results from generator loading

The effects of operating at a unity power factor from full load to no load is presented. It is observed that the terminal voltage and frequency increases whiles current decreases with decrease in loading as shown in the Fig. 9, Fig. 10 and Fig. 11 respectively.

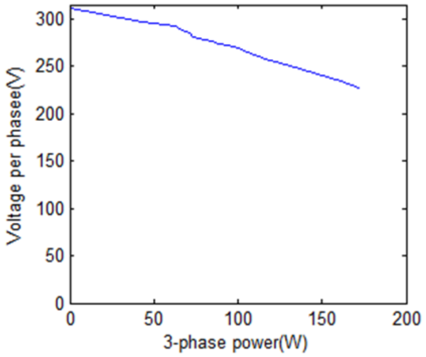

Fig. 9 Voltage variation with load

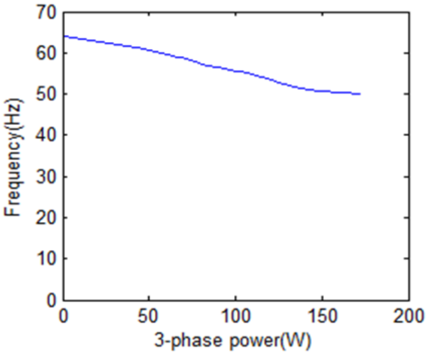

Fig. 10 Frequency variation with load

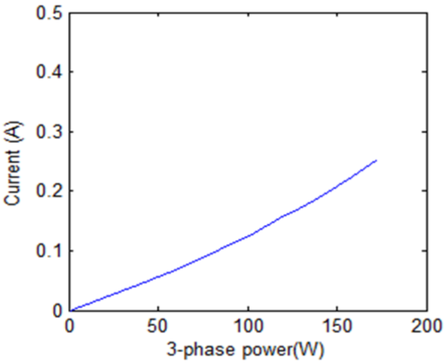

Fig 10. Current variation with load

III. DISCUSSION

The results from the generator loading clearly depicts what is expected in a MHPP. As expected, when the load on the generator is reduced there is a drop in current due to the increase in resistance of the 3-phase rheostat.

Again it can be seen that the frequency has increased to a very critical value which is unacceptable in the frequency control of power system. The increase in frequency is as a result of decrease in generator load.

Also since the terminal voltage is function of field excitation and frequency is in (3) it is expected that an increase in frequency due to the reduction in generator load will cause the terminal voltage to increase.

In most power generation stations, it is required that the terminal voltage is kept nearly constant under varying loads. This, in most cases, an Automatic Voltage Regulator (AVR) is used to control the excitation current of the synchronous generator so as to keep the terminal voltage constant. The synchronous generator used for this experiment has no AVR installed hence the terminal voltage varies with load as expected.

IV. CONCLUSION

The results from this study clearly shows that decreasing the load on the synchronous generator in a MHPP using a resistive balanced load increases the terminal voltage and the frequency. To avert the problem of increase in frequency, an ELC can be used. This will maintain the load at the generator output constant under various consumer load by diverting excess power to a resistive damper load, consequently maintaining the total load on the generator constant.

The ELC is currently being designed for a MHPP. This after implementation will be beneficial to remote communities in Kenya because they will have a continuous and uninterrupted power supply at rated frequency and voltage and also free power from the national grid for other industrial uses.

APPENDIX

TABLE II
DATA FROM GENERATOR LOADING

No.	Vp-p(V)	I(A)	F(Hz)	W3 ϕ (VA)	PF
1	227.9	0.251	49.92	171.61	1.0
2	234.2	0.230	50.20	161.60	1.0
3	241.4	0.204	50.69	147.73	1.0
4	248.2	0.184	51.42	137.00	1.0
5	252.9	0.165	52.69	125.20	1.0
6	256.4	0.154	53.91	118.45	1.0
7	265.8	0.130	55.40	103.66	1.0
8	270.0	0.123	55.64	99.63	1.0
9	271.7	0.116	56.14	94.37	1.0
10	274.3	0.108	56.63	88.87	1.0
11	275.9	0.102	56.95	84.43	1.0
12	278.6	0.096	57.35	79.89	1.0
13	279.2	0.091	57.84	76.22	1.0
14	281.3	0.087	58.24	73.37	1.0
15	284.6	0.084	58.60	71.21	1.0
16	286.4	0.080	58.92	68.73	1.0
17	289.7	0.075	58.98	65.18	1.0
18	292.7	0.072	59.37	63.22	1.0
19	296.5	0.047	61.27	42.52	1.0
20	310.9	0.000	63.87	0.00	0.0

REFERENCES

[1] Practical Action. [Online]. Available: hppts//practical_ action.org/docs /technical_information _service/micro_hydro_power.pdf

[2] P. Garman, Water current turbines, Russell Press Ltd., Nottingham, UK, 1986

[3] P. Tamrakar, "Development stages of ELC for micro hydro power plant, E-novation, Vol. 2, pp- 1, 2002.

[4] K. Kihato, J. N. Nderu, and G. M. Hinga, "Motor speed measurement using magnetostrictive amorphous wire," *Proceedings of 2007 JKUAT Scientific, Technological and Industrialization Conference*, pp. 315–319, October 2007.

[5] C. K. Kitur, J. N. Nderu, A. M. Muhia, "Frequency sensing of an isolated pico-hydro power generation plant using magnetostrictive amorphous wire", *International Journal of Emerging Technology and Advanced Engineering*, pp. 1-5, Vol.2, 2012.

[6] Y. K. Chauhan, S. K. Jain and B. Singh, "A prospective on voltage regulation of self-excited induction generators for industry applications", *IEEE Transactions on Industry Applications*, Vol.2, pp. 720-730, 2010.

[7] A. M. Muhia, "Speed control of single-phase induction motor using fuzzy logic technique with magnetostrictive amorphous wire speed sensor", M.Sc. Thesis, Jomo Kenyatta University of Agriculture and technology, Kenya, 2013.

[8] P. Kundur, J.B. Neal, and G.L. Mark, "Power System Stability and Control", McGrawHill, 1994.

[9] B. S Guru ,H. R. Hiziroglu, Electric machinery and transformers. 3rd ed. New York, USA: Oxford University Press, Inc., 2001.