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POWER HARVESTING FROM FLUID FLOW IN PIPELINES USING TURBINE-BRUSHLESS GENERATOR SYSTEM

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ABSTRACT

This work investigates the possibility of using small turbine to utilize the kinetic energy of fluids in pipeline using electromagnetic mechanism. This is to device a constant means of power supply to pipeline monitoring sensors, from the surrounding system. The design employed the use of a small turbine of 4.6cm directly attached to a brushless DC generator. The proposed system is modeled and simulated using Mat Lab/Simulink software. Simulation results analysis using maximum power point tracking (MPPT) control are investigated and analyzed. The result shows that the proposed system can generate about 5Watts of power, enough to be used for a large sensor system within the pipeline.

Keywords: Electromagnetic; Power Scavenging; Kinetic Energy; Turbine Brushless Generator, Maximum Power Point Tracking (MPPT).

1. INTRODUCTION

Pipelines are among the most efficient, cost-effective and environmental friendly means of fluid transportation, often deployed for the transportation of oil, gas and petroleum products with long portions of the pipes passing through remote areas.(Dubey, 2010). Despite all these advantages, they are vulnerable to damage either due to human or environmental factors. This damage, if unreported or not addressed, can lead to eventual catastrophic failure of the pipeline system, loss of containment or inventory, ecological disaster and disruption of the product supply with huge safety and economic consequences. Hence, it is imperative that the pipeline system be monitored securely.

In recent years, there have been significant advances in Wireless Sensors Network (WSN) technology, making it possible for oil and gas companies to deploy WSN on pipeline systems to improve safety and efficiency (Awawdeh, 2006) However, monitoring pipeline system using wireless sensors demands continuous function or long-term power supply. The power supply commonly employed in many wireless sensor systems uses batteries (Emilio, 2009). However, conventional batteries have short lifespan after which they must be physically replaced by human intervention; otherwise the system cannot continue to function efficiently.

Advances in technology have led to more efficient techniques that provide almost unlimited power supply for such electronic devices. The power requirements for sensors are reduced to the range of tens to hundreds of milliwatts (Weimer, 2006). This is one possible solution for long, continuous power supply for some applications. Despite this improvement in technology, it is however, not keeping pace with the increasing demand in wireless sensor network applications (Gilbert, 2008).

As the demand for deployment of autonomous sensors and sensor networks is growing, this leads to a subsequent increase in the demand for localized, independent energy harvesting capabilities for each node. For this reason, localized remote-area power harvesting techniques have become an important amendment to sensors employed in pipeline systems in order to extend the time a remote sensor node can operate. Thus, the only reliable approach that can supply an unlimited power is to use power harvesting capability at the sensor network environment.

2. LITERATURE REVIEW

There are various ways of harnessing energy from the environment depending on the ambient condition where the sensor has been deployed. Electricity can be sourced from the flow of any fluid (gas or liquid) in a variety of techniques. At the macro scale, the use of wind turbines is becoming more common (Ali, 2015). However, at the scale needed for sensor networks, novel approaches are required, due to viscosity effects (Moraisa, 2008).

The energy of moving liquids in pipes, such as water or liquid nutrients, utility gas and petroleum products, can be harvested with small-size turbines. This approach can be explored to supply energy to small electronic devices for monitoring sensors attached to the pipeline. Similar research was conducted by in pipes of irrigation control systems as power outlets within the crops. The authors (Mohamed, 2011) run a small-size hydro generator with the turbine. While connecting such types of turbine may affect the fluid flow in the pipes, and due to large inertia it may be difficult to turn in the case of gaseous fluid. A similar piece of research work has been carried out in , in which piezoelectric material was employed using an experimental approach. The work only predicted that the flow can be utilized to scavenge power but there was no specific value of power reported.

In this paper, an energy harvesting system is proposed, which utilizes a small turbine to harvest fluid energy from pipeline flow to power its associated electronic circuitry.

3. POWER HARVESTING TECHNIQUES

There are broad ranges of conversion devices available to convert any motion based energy source like the fluid flow into electric energy. The three main conversion mechanisms are:

i. Piezoelectric, has the advantage of direct generation of desired voltage but difficult to integrate in micro-system, brittle in nature and sometime leak prone.
ii. Electrostatic, readily implemented in standard micro-machining processes, but has the disadvantage of requiring separate voltage source.
iii. Electromagnetic, has and improved reliability and reduced mechanical damping its disadvantages are bulky in size and that Electromagnetic method is more reliable and efficient (Sinha, 2005) and thus chosen in this research to improve the power output.

3.1 The Proposed Design

This design consists of a small turbine directly connected to brushless DC (BLDC) generator, employing a three-phase two-pole AC permanent magnet synchronous generator. The said arrangement is to be attached to an in-line pipe attached to the main pipeline. The in-line pipe has an inlet and outlet flows, which turns the small turbine. The turbine performance which depends on the coefficient of power, C_p, which depend on the pressure variation between the inlet and outlet flows through and out of the in-line pipe. The more pressure difference the more power that could be generated, but because the power required is not much, a small variation of 63Pa is adopted as in (Soga, 2011).

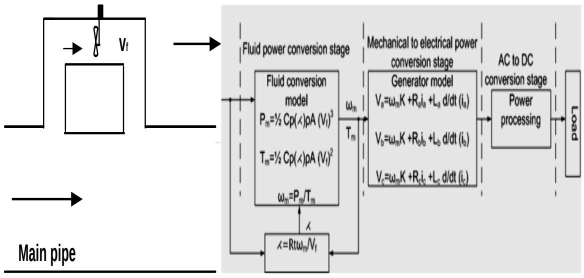

Figure 1: The overall functional block model of the proposed system

4. CONVERSION OF PIPELINE FLUIDS FLOW KINETIC ENERGY TO ELECTRICAL POWER

Converting the kinetic energy present in the flow into electrical energy requires an intermediate mechanical energy converter turning this kinetic energy into a relative movement between two parts; this kinetic-to-mechanic conversion can be achieved using a horizontal axis turbine. The mechanic-to-electric conversion is achieved by electromagnetic method. The small pipe flow velocity is assumed to be twice as the main pipe flow velocity. The power density from the fluid by the turbine is define as (Bansal, 2009; Howey, 2011)

$$P = \frac{1}{2}\rho {v_f}^3 \quad \ldots \quad (1)$$

Where ρ is the fluid density, v_t is the fluid-flow speed. The kinetic power of the unperturbed fluid over a cross sectional area A is given as

$$W = \frac{1}{2} A\rho {v_f}^3 \quad \ldots \quad (2)$$

The performance coefficient, C_p is determined by a factor c, called the interference factor which is define as the ratio of the downstream speed in the area normal to the fluid flow, to the upstream speed The performance coefficient is a dimensionless measure of the efficiency of a turbine in extracting the energy content of a fluid stream(Ragheb, 2011).

$C_p$is given by

$$C_p = \frac{P}{W} = \frac{1}{2}(1 - c^2)(1 + c) \quad \ldots \quad (3)$$

Where, c is given by the ratio of the downstream wind speed v_2 and the upstream speed v_1 as

$$c = \frac{v_2}{v_1} \quad \ldots \quad (4)$$

The interference factor is assumed to be the ratio of the in-plane pipeline flow speed v_f to the main pipeline flow speed. v_p.thus c is defined as

$$c = \frac{v_f}{v_p} \quad (5)$$

The ratio for such hypothesis is assumed to be 1:2, meaning that the speed of fluid flow speed of the main pipeline is twice that of the in-plane pipe speed. Therefore, c can be calculated as follows:

$c = \frac{1}{2}$ Using our assumption then $C_p = 0.54945$

To harness power from the fluid flow in pipeline using turbine, the governing equation presented above is employed for energy conversion using turbine from the fluid as given by (Gao, 2006). The performance coefficient, Cp as a function of the interference factor c is given in figure

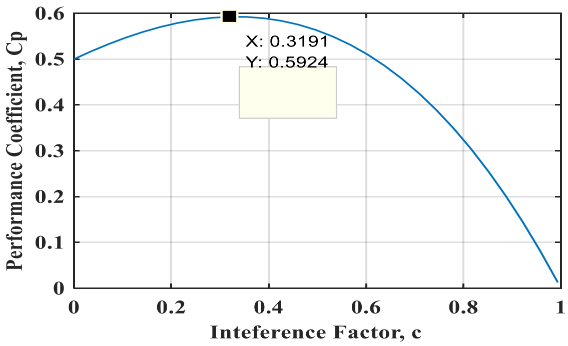

Figure 2: Power coefficient of turbine and fluid speed

When c = 1, $v_f = v_p$ and the flow is undisturbed, leading to a performance coefficient of zero. It can be noticed from the graph that the performance coefficient reaches a maximum around c = 0.3191. The power that can be generated is given by

$$Pt = \frac{1}{2}\pi R_r{}^2 \rho v_t{}^3 C_p \quad \ldots \quad (6)$$

where: Pt is the output power extracted by the turbine (W), ρ is the density of the fluid (Kg/m^3) R_t is the radius of the turbine-rotor blades (m), V_f is the fluid velocity (m/s).Another important concept relating to the power of turbines is the tip speed ratio, which is defined as the ratio of the fluid speed V_f and the turbine speed v_t is as given in equation (7) as in (Weimer, 2006) .

$$\lambda = \frac{v_t}{v_f} \quad \ldots \quad (7)$$

Also,

$$v_t = R_t \omega_t \quad (8)$$

Where, ω_t and R_t are the turbine angular velocity, and the blade radius respectively. As stated in (Twidell, 2006) thus:

$$\lambda = \frac{R_t \omega_t}{v_f} \quad (9)$$

From equation (9) if λ is kept constant, the rotational speed ω_t should directly vary with the fluid speed, v_t. Figure (3) depicts simulation of equation (9) in Mat lab at constant TSR, the fluid speed and turbine rotor speed tested over varying fluid speed.

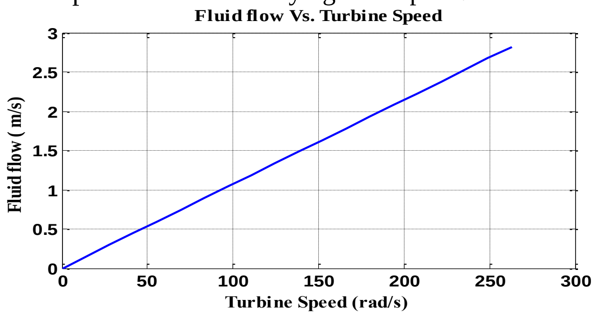

Figure 3: Relationship between fluid speed and speed of the turbine shaft

The turbine speed V_f is determined using the pipeline design as given in Table 2, as follows:

$$v_f = \frac{F_r}{A_p} \quad \ldots \quad (10)$$

Where: F_r is the volumetric flow rate of the fluid, in (m^3/sec) and A_p is the area of the pipe. The cross-sectional area of the pipe can be determined using the radius of the pipeline as given in equation (11).

$$R_p = \frac{S_p}{2} \quad \ldots \quad (11)$$

Where:S_p is the pipe size given in (m).

To study the relationship between $C_p$and V_f a characteristic curve plot for the power coefficient of the turbine over a range of fluid speeds for a two-bladed rotor is depicted in Figure 4, using equation (6). It can be seen that as fluid speed increases, the power coefficient of the turbine also increases, the increment is shown to increases slowly between the speed of 0 and 0.8m/s, then increases in proportion with the coefficient until it reaches a maximum value of 2.8m/s this shows that more fluid power is harvested by the turbine at higher flow speed.

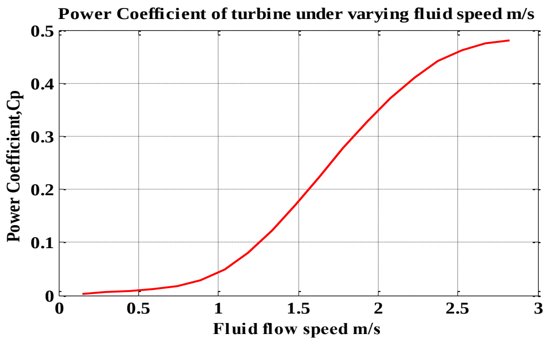

Figure 4: Power coefficient of turbine and fluid speed

These values are chosen since small flow-driven energy scavengers exhibits low efficiency because of high viscous losses (Bansal, 2009). Therefore since fluid through pipeline can either be liquids or gases as compared to air in wind turbines and water in tidal/marine turbines, the power coefficient for tidal kinetic energy in ideal condition was 40% but, the average coefficient of power is between the range of 25% to 30% in normal operation as reported in (Kirke, 2006.). The range of speed for tidal flow used in power harvest is found to be in the range of, 0.8 to 3.0 (Kirke, 2006.), and the pipeline flow speed is calculated to have an average value of 2.8.

4.1 Turbine and Generator Dynamics

The mechanical to electrical conversion employed in this study is a small brushless dc generator, coupled to the turbine. A brushless alternator has several advantages over the brushed type, including higher efficiency and reliability, reduced noise, a longer lifetime (no brush erosion), and more power (Park 2012). The Per phase, equivalent circuit of the generator is shown in Figure 5 and AC voltage model at the generator output is given by

$$V_g = R_g i_g + L_g \frac{d}{dt}\left(i_g\right) + e_g \quad \ldots \quad (12)$$

Where:

L_g is per phase Stator inductance

R_g Stator resistance

$e_g = \frac{2}{p}\omega_e \Psi_{pm}$ is the Back emf Ψ_{pm} is permanent magnet flux ω_e Is the electrical frequency

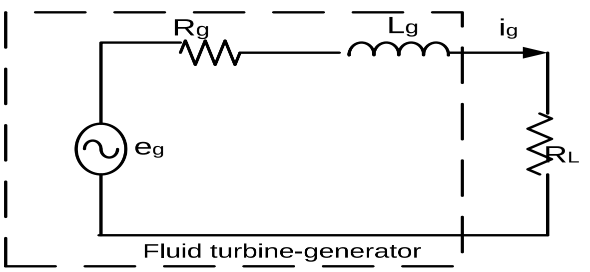

Figure 5: Generator equivalent circuit

There are two electrical output variables of the generator that are closely related to the rotational speed of the generator rotor ω_g and hence the fluid speed. These are: 1) the generated voltage V_g and 2) the electrical frequency f of the voltage, V_g Since a direct coupling of the turbine and generator rotor is assumed then,

$$\omega_g = \omega_t \quad \ldots \quad (13)$$

Therefore

$$\omega_g = \frac{\lambda v_f}{R_t} \quad (14)$$

The equations that relate the two electrical variables with respect to the incoming fluid speed can be expressed as follows:

$$e_g = \frac{2}{p}\omega_e \Psi_{pm} = \omega_t \frac{\lambda v_f}{R_t} \quad \ldots \quad (15)$$

$$f = \frac{\rho\lambda}{4\pi} v \quad \ldots \quad (16)$$

With the model equation 6 to 16 an initial designed variables calculation was conducted as given in Figure (1), from which the following studies are carried out.

a. The fluid flow speed and the rotational speed of the turbine shaft.
b. Power generated within the a range of fluid speed
c. Power coefficient of the turbine versus the fluid speed

4.2 Model Implementation

A schematic of the complete fluid generator simulation model is depicted in Figure (6).The model comprises a variable speed turbine directly driving a brushless DC generator and MOSFET drive-switching converter. The model design implementation is given in this section. The whole concept is simulated using MatLab using Simulink.

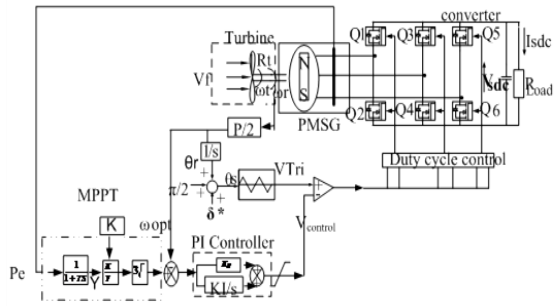

Figure 6: The overall Simulink model set up

5. RESULTS AND DISCUSSIONS

The design considered using a brushless DC generator whose rotating speed was chosen to tally with the rotating speed of the turbine shaft. The designed voltage for the generator was higher than the turbine designed parameters (table 3). Therefore a number of simulations are conducted, using different values of DC voltage, in order to study the design and to determine the best matching parameters especially for the speed and power requirements.

At 4V DC voltage the system was found to give values very close to the turbine design and thus employed as the system working voltage. A test fluid flow speed from a typical pipeline system was employed to test the system design. The close loop simulation with MPPT control; the simulation results reveal that considerable amount of power sufficient to derive and sustain a sensor node.

From the simulations, harvested fluid power from the turbine (Pm) fed to the generator, and the equivalent electrical AC output power from the generator, (Peg) is obtained at the output of the generator. The raw electrical AC power is fed to the converter unit where regulated DC voltage is obtained at the output of the converter to charge the battery (load).

Figure 7 shows the power level at different stages of the power-processing unit according to the fluid speed. It can be observed that between the turbine power (Pm) and the electrical (DC) power there is a relatively small loss which increases as the power increases, and can be attributed to the switching losses. There is also a considerably large power difference between the turbine power and generator output power. This can be due to the friction within the generator.

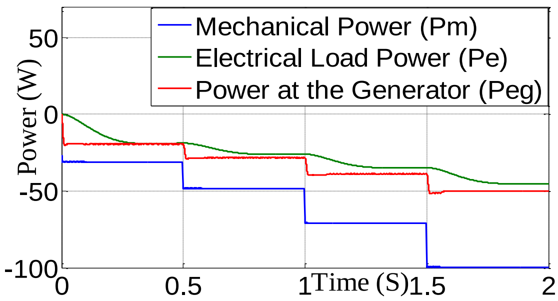

Figure 7: mechanical/AC electrical/DC electrical DC Power (P_m/P_{eg}/Pe), , d) generator output Phase current.

Figure 8 and 9 show the stator current and voltage AC waveform at the generator output, varying with the fluid flow. Figure 8 include the output DC voltage at the battery compared with the AC voltage, whereby the AC varies but the voltage at the capacitor storage remains constant.

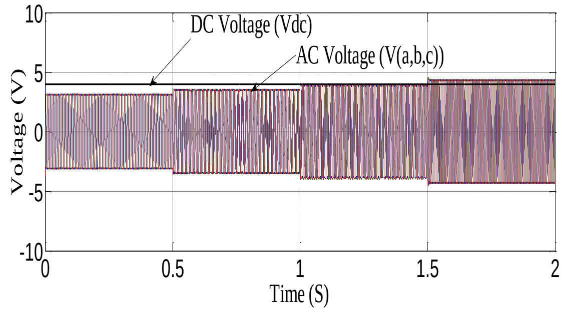

Figure 8: generator output voltage AC($v_{(a,b,c)}$) and DC($v_{(DC)}$) voltage

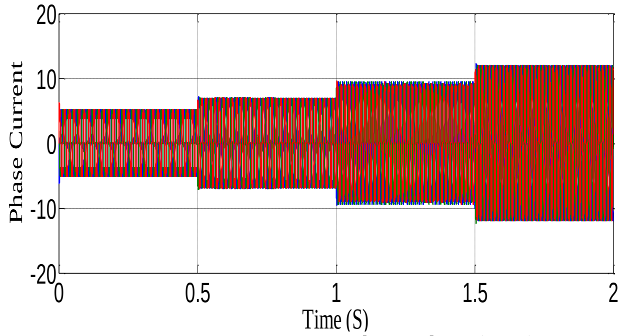

Figure 9: generator output AC and DC voltage ($v_{(a,b,c)}$)

Figure 10 depict a detail of the phase current while Figure 11 illustrates the turbine flow characteristics at different flow speeds, and the extractable power is calculated based on Equation (3). In this figure, the blue line is the MPPT control strategy curve. Therefore, when the fluid speed changes the speed response from the generator can be seen to track the reference speed with some overshoot at the transition stage, in order to maintain a constant torque.

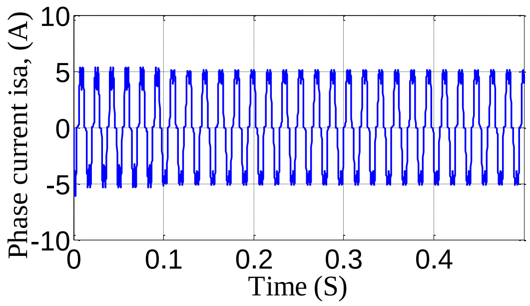

Figure 10: three phase ($i_{(a,b,c)}$) with single phase

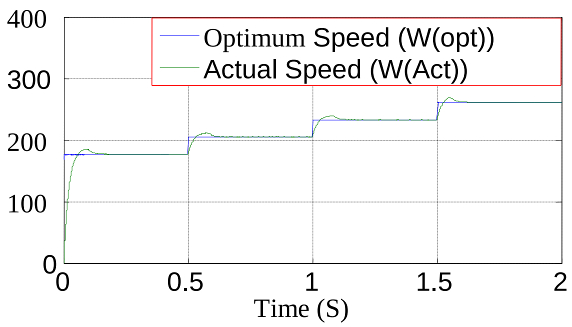

Figure 11: generator optimum rotor speed/ generator actual rotor speed ($\omega_{(opt)}$/$\omega_{(act)}$),

6. CONCLUSION

The proposed design, considers an effective way of power generation from fluid flow using a turbine generator. The method employed have advantage over the other approaches stated earlier, this is evident as the power in [8], employing used piezoelectric method can generate 9.3mW while in this approach about 5Watts can be generated, enough to operate sensors However limitation in this approach is proper regulation system to maintain a constant power level for the microelectronics circuit when the fluid flow changes. This warrants the integration sensor node system that will form a network of sensors with power module for an unlimited power supply to the sensors.

Neglecting loss in the direct coupling between the rotor shafts and the turbine, the electric generator, there is a direct linear relationship between the incoming fluid speed and the rotational speed of the electric generator; this paves way for indirect fluid speed sensing approach by measuring the equivalent electrical voltage or frequency output from the generator.

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