A Magnetic-Geared Generator for Pico-Hydro Power Generation Application

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ABSTRACT

This paper proposes a magnetic-geared generator which has a dual-pole piece configuration in a double-stator magnetic geared machine, for pico-hydro renewable energy power generation application. A high power density is achieved when a coaxial magnetic gear is integrated with a high-speed double-stator permanent magnet brushless generator. The operating principle is described and verified by simulation using 2D-finite element analysis method. The prototype is evaluated by experiment and it is found that the generator achieved a maximum output power of 360W at speed of 500 rpm and efficiency of 62% respectively. The performance results verify the validity of the proposed generator design.

Keywords: Magnetic-geared generator, pico-hydro, prototype, power, renewable.

INTRODUCTION

Studies have shown that there is a strong relationship between poverty in remote rural areas and access to electricity (Williamson, Stark & Booker, 2014). Electricity access is essential for the provision of clean water, good sanitation and healthcare in ensuring a high standard of living. Most households in rural areas without a connection to the electrical grid use kerosene lamps for lighting. However, this source of light energy is inefficient and hazardous because kerosene lamps emit carbon gases such as; carbon monoxide, nitric oxides and sulphur dioxide which are harmful to the environment (Ariadna & Cathryn, 2020). A study by the International Energy Agency found that only 65.1% of rural areas in developing countries had to access to electricity due to the high cost of connecting electric grids to low-density remote areas (Maximo, 2015). The conventional sources of non-renewable energy such as coal, oil, gas are reducing daily but renewable energy technologies are clean and contribute to the reduction of greenhouse gas emissions (Ramchandra, Vittorio & Rabani, 2020). Hydro power as one source of renewable energy possesses great potential energy which can be harvested and converted to electrical power (Falcão, Henriques & Gato, 2017). Pico-hydro power generation can address problems of rural areas with no access to electricity by providing rural electrification (Basir Khan, Pasupuleti & Jidin, 2015). A study (Williamson, Stark & Booker, 2014) found that pico-hydro power generation less than 5 kW was projected to be 25% cheaper for off-grid generation after ten years. In order for pico-hydropower generation to be competitive with existing power generation technologies, the system should be cheap, efficient, reliable and environmentally clean (Henderson, 2006). Hydropower generation systems are analogous to wind power generation technologies that are used for wind power harvesting. Pico-hydropower generators should generate electricity at low-speeds of 200 rpm, flow rate of 1-10 m^3/s and low head of water from 1-3.5 m (Harvey, 1993). To harvest electrical energy from hydro power energy, the hydro energy is first converted from potential energy to kinetic energy and then electric energy by using electrical generators. Low-speed direct drive power generators with operating speeds of 200-500 rpm would be suitable but large in size and cost. One solution is to couple a mechanical gearbox to the input shaft of the generator to increase the rotating speed of the generator. However mechanical gearboxes have problems of maintenance, noise and oil lubrication (Dobzhanskyi et al., 2019). Recently, research on magnetic gearing and magnetic geared PM machines have generated a lot of interest in the last decade because magnetic gears are potential new emerging technologies to replace mechanical gears and address problems of oil, lubrication, friction, non-contact torque transmission and inherent overload protection. The concept of integrating a magnetic gear with a conventional PM machine results to a new class of magnetic geared PM electrical machines which can be designed as magnetic geared generators (Johnson, Gardner & Toliyat, 2017). Researchers (Chen et al., 2021), (Kjaer et al., 2019) have proposed a magnetic geared generator for wind power generation applications. Magnetic geared low-speed power generators are favourable for pico-hydro power generation applications because of their reliability, lower acoustic noise and non-contact transmission torque compared to mechanical geared generators.

This paper presents the power performance characteristics of a magnetic gear integrated with a double-stator PM generator for pico-hydro power energy harvesting application. One of the main challenges of remote rural areas is access to electricity and the electric grid. In this paper, a solution proposed to address this problem is a low-speed generator with a low head of water which can provide renewable energy technology for remote rural areas that are not connected to the electric grid. To verify the validity of the proposed MG generator, a prototype is constructed and tested in the laboratory. Section 2 explains the range of pico-hydropower operation. Section 3 of the paper describes the structure and operating principle of the MG generator. Section 4 presents the results and discussion and finally the conclusions are presented in section 5.

Operational Range of Pico Hydropower Systems

The key parameters that determine the selection of a turbine generator for pico hydropower applications are; head of water, output electric power and output shaft speed (Alexander & Giddens, 2008). Most of the commercially available pico-hydro generators can generate electric power below 5 kW at high, mid and low head of water. The use of conventional 4-pole or 6-pole generators limits their use for pico hydro turbine application. Though a low speed generator can be designed with an operating speed of 50 rpm or 200 rpm to replace the conventional 4-pole or 6-pole generator, pico hydro power generators with a low head specification can be installed in remote areas that are not connected to the electric grid to address problems of rural electrification. The pico range of hydropower systems which is used to aid the selection of a suitable hydro turbine generator as reported by (Williamson, Stark & Booker, 2014) is shown in Figure 1.

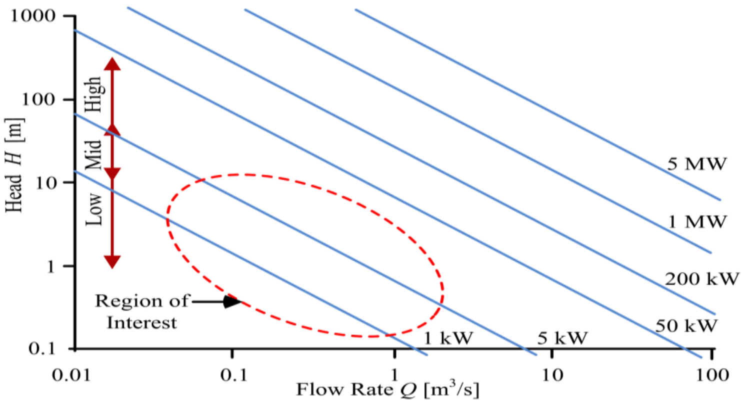


Figure 1. Characteristic range of various pico-hydropower systems with head of water specifications (Williamson, Stark & Booker, 2014)

Description of the Magnetic Geared Generator

The structure of the magnetic geared generator is shown in Figure. 2. It consists of three permanent magnet (PM) rotors, two iron ring pole pieces and two stators. The middle rotor is the low-speed prime mover while both high-speed outer and inner rotors hold the field permanent magnets. A mutually magnetically coupled configuration as demonstrated in (Salihu et al., 2017) is achieved by integrating the magnetic gear with the generator. The mechanical assembly is illustrated in Figure 3 and it can be observed that the three PM rotors rotate independently in the axial direction. When the low-speed prime rotor rotates, both inner and outer rotors rotate synchronously opposite in direction to the prime rotor according to the gear ratio. The field permanent magnets induce excitation in the coil windings to produce an EMF therefore resulting to electrical power generation. The design specifications of the magnetic geared generator are listed in Table 1 while the material properties of the generator are given in Table 2.

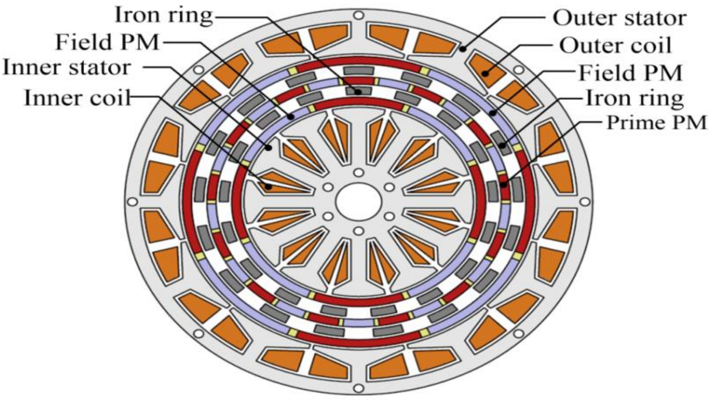


Figure 2. Structure of the magnetic geared double-stator PM generator.

For the selection of the magnetic gear ratio the number of pole pairs of permanent magnets selected for the prime rotor is 13, while for both outer and inner rotors is4 respectively. This pole pair combination produces a gear ratio of 3.25 and a cogging torque factor of $C_f = 1$ as described in (Praslickaet al., 2021) and C_f is expressed as:

$$C_f = \frac{2P_{\text{field}}N_{\text{iron}}}{LCM(2P_{\text{field}}N_{\text{iron}})} \qquad (1)$$

Where N_{iron} is the number of iron pole pieces and *LCM* is the smallest common multiple between the number of field PMs and number of iron pole pieces. According to the magnetic gearing principle (Matthew et al., 2021), the magnetic gear relationship between the angular speed ratio of number of pole-pairs and the airgap flux density space harmonics are governed by:

$$\omega_{\text{prime}} = \frac{p_{\text{prime}}}{|p_{\text{prime}} - p_{\text{iron}}|}\omega_{\text{field}} + \frac{p_{\text{iron}}}{|p_{\text{iron}} - p_{\text{prime}}|}\omega_{\text{iron}} \qquad (2)$$

$$p_{\text{field}} = |p_{\text{iron}} - p_{\text{prime}}| \qquad (3)$$

where ω_{field}, ω_{prime}, and ω_{iron} are the angular speeds of the field PM rotor, prime PM rotor and iron pole pieces respectively, while p_{prime}, p_{field}, and p_{iron} are the pole pairs of prime PMs, field PMs and number of iron pole pieces respectively. The magnetic gear ratio G_r can be expressed as:

$$G_r = -\frac{\omega_{\text{prime}}}{\omega_{\text{field}}}\bigg|\omega_{\text{iron}=0} = \frac{p_{\text{prime}}}{p_{\text{field}}} \qquad (4)$$

The negative sign indicates that both outer and inner PM rotors rotate in the same direction opposite to the prime PM rotor. The mechanical assembly of the MG generator is shown in Figure 3.

Table 1. Design specifications of the proposed MG generator.

Parameter	**Dimension**
Outer and inner airgap lengths	1.0 mm
Outer stator outside diameter	150 mm
Outer stator inside diameter	116.6 mm

Inner stator outside diameter	74.6 mm
Inner stator inside diameter	14.0 mm
Axial length	30.0 mm
No. of outer and inner stator slots	12
No. of outer and inner field PMs	8
No. of prime PMs	26
No. of outer and inner pole pieces	17
Active volumetric density	393 cm^3

Table 2. Property of materials and winding specifications

Component	**Material**
Magnets	Nd-Fe-B-38H
Pole pieces	SS400
Rotors	SS400
Stators	50H800 Laminated steel
Diameter of wire	0.80 mm
Number of turns outer coil	75
Number of turns inner coil	31
Resistance per phase outer coil	1.70 Ω
Resistance per phase inner coil	0.80 Ω
Phase connection	Star

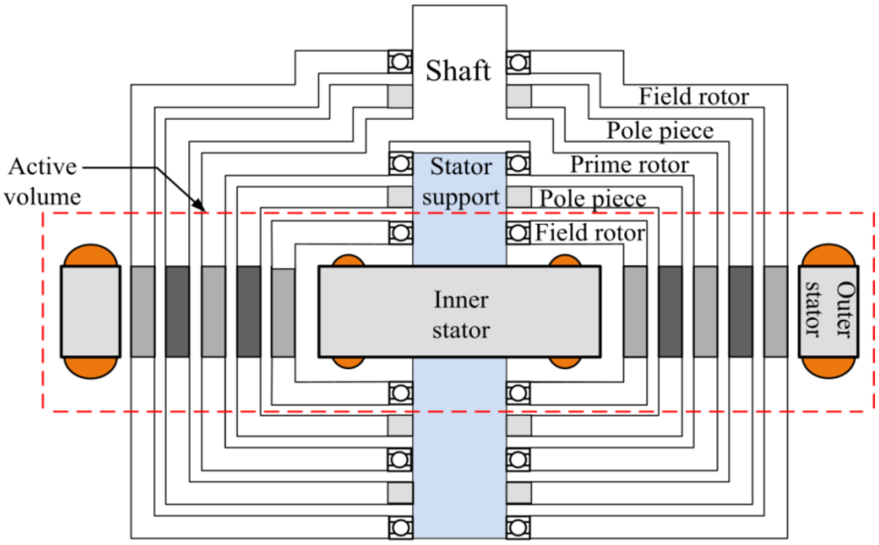


Figure 3. Mechanical assembly of the prototype

RESULTS AND DISCUSSION

Prototype Assembly

A frontal view of the fabricated magnetic geared generator is shown in Figure 4. To shield the PMs from centrifugal forces at high speeds, aluminium end rings are secured on each end of the PM rotors. Although, this design results to eddy current loops between the aluminium end rings and ferromagnetic pole pieces. The scope of this research work was aimed for low-speed power generation therefore this factor was ignored.

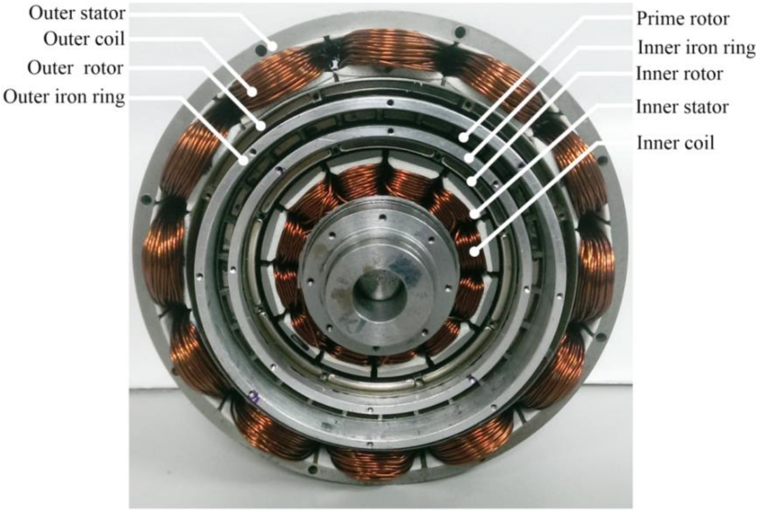
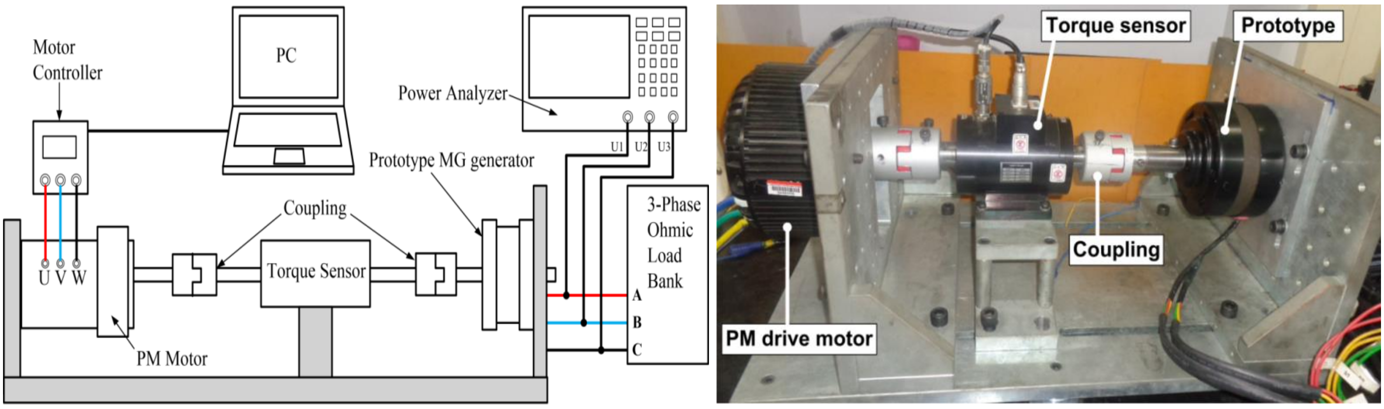


Figure 4. Prototype assembly of the magnetic geared generator

Experimental Setup

The block diagram and experimental setup for measuring the electrical power dissipated by the magnetic-geared generator is shown in Figure 5(a) and Figure 5(b) respectively. The magnetic-geared generator was connected to a balanced three phase resistor load bank while the electrical power produced was measured with a Hioki power analyzer. The torque, speed and power are experimentally measured at various prime rotor speeds.



(a) (b)

Figure 5. Measurement setup. (a) Electric power measurement block diagram. (b) Test rig with prototype.

On-Load Voltage and Current Characteristics

The voltage and current waveforms with a resistive load of 62 ohm per phase at constant prime rotor speed of 200 rpm are shown in Figure 6. It can be observed that the predicted results correlate well with the measured results. Though third-harmonics are dominant in the phase voltage and current waveforms which are a general feature with concentrated windings and the pole-slot selection. The peak phase voltages from the calculated and measured results are ≈ 42 V and ≈ 41 V, while the calculated and measured peak phase currents are ≈ 0.69 A and ≈ 0.66 A respectively.

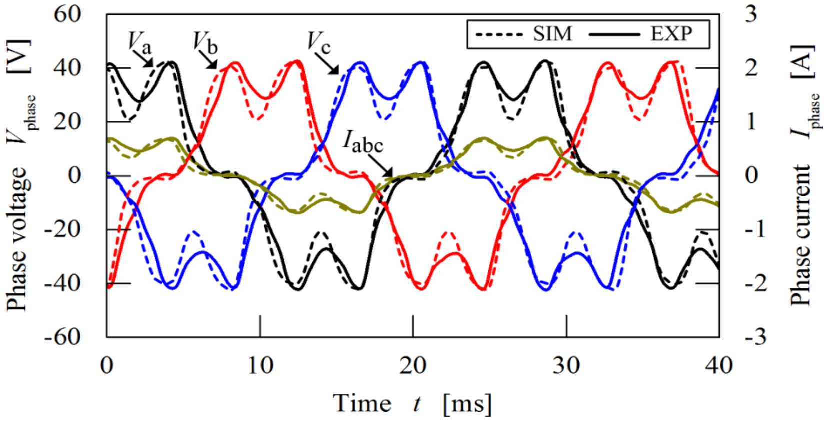
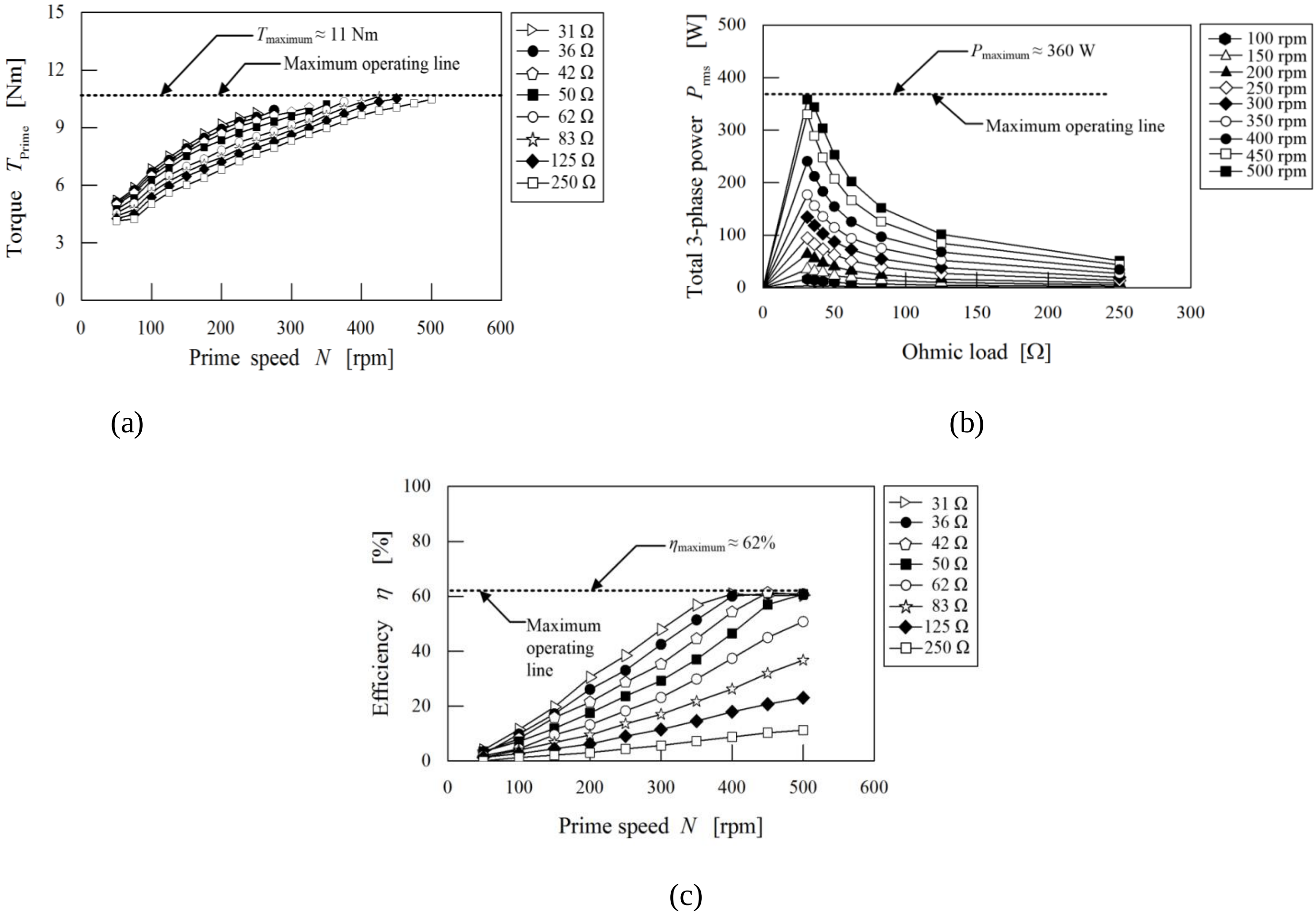


Figure 6. Comparison of simulated and measured three-phase voltage and current waveforms output from the MG generator with resistive load of 62 Ω at prime rotor speed = 200 rpm.

Torque, Power and Efficiency Characteristics

The maximum torque achieved by the MG generator shown in Figure 7(a) is ≈ 11 Nm with resistive load of 83 ohm at prime rotor speed of 425 rpm. The total maximum active AC power dissipated by the generator shown in Figure 7(b) is ≈ 360W at prime rotor speed of 500 rpm with resistive load per phase of 31 ohm. The maximum efficiency achieved by the MG generator as shown in Figure 7(c) is ≈ 62% with resistive load of 42 ohm at 450 rpm.



(a)

(b)

(c)

Figure 7. Torque, power and efficiency characteristics. (a) Torque as function of prime speed. (b) Power as function of resistive load. (c) Efficiency as function of prime speed.

CONCLUSION

A magnetic geared generator for pico-hydro power energy harvesting has been presented in this paper and a prototype has been developed using a magnetic gear integrated with a double-stator permanent magnet machine. The electrical power characteristics have been measured with different resistive loads at various prime rotor speed. It was found that the magnetic geared generator produced a maximum electrical power of 360 W at low-speed of 500 rpm. On the basis of the above performance, the magnetic geared generator is suitable for pico-hydro power generation application if both the efficiency and power are improved. More research needs to be conducted on the scalability of this renewable energy technology so that it can produce adequate power and save the environment from carbon emissions produced from fossil fuels based generators.

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