Design, Simulation, and Performance of Afsrg 8/8 in an Electric Power Generation System with Low Speed Drive

Rafles Prasuki Pasaribu[1], Parlin Siagian[2], Rahmaniar[3]
Universitas Pembangunan Panca Budi. Medan, North Sumatera, Indonesia
Email: parlinsiagian@dosen.pancabudi.ac.id

Low-speed micro-hydro power plants require generators with high starting torque, good efficiency, and the ability to operate at low rotational speeds. This study designs and builds an Axial Flux Switched Reluctance Generator (AFSRG) with an 8/8 configuration to address those needs. AFSRG was chosen for its simple structure, robustness, and magnet-free operation. The methodology included geometric design using CAD software, electromagnetic simulation using FEMM, and experimental testing in a micro-hydro setup. The results show that the 8/8 AFSRG can generate 48V at 300 rpm with a system efficiency of 78%. AFSRG is feasible for use in remote micro-hydro power generation applications with low-speed water flow.

Keywords: AFSRG, axial flux, switched reluctance generator, micro hydro, low speed

Corresponding Author:
Rafles Prasuki Pasaribu
Universitas Pembangunan Panca Budi. Medan, North Sumatera, Indonesia

1. Introduction

Energy challenges in Indonesia remain crucial, particularly in remote areas, small islands, and hilly areas not yet fully covered by the national electricity grid (PLN). High dependence on fossil fuels such as coal and oil makes Indonesia's energy system vulnerable to price fluctuations and negatively impacts the environment. Yet, Indonesia has significant potential for new and renewable energy (EBT), one of which is microhydro power. Indonesia's microhydro power potential is estimated at 19,385 MW, but currently only around 326 MW, or less than 10%, is utilized (EBTKE, 2020).

Microhydro power is highly suitable for Indonesia due to its geographical characteristics, rich in rivers and hilly terrain. This technology can provide electricity independently and sustainably to rural communities without relying on the central grid. Besides being environmentally friendly, microhydro power also has low operating costs and a long operational life. With optimal utilization, microhydro power can be an alternative solution to support national energy security and achieve the target of a 23% renewable energy mix by 2025 [1].

Conventional generators, such as synchronous and induction generators, are generally designed to operate optimally at high speeds, typically above 1,000 rpm. When operated at low speeds, the efficiency and performance of these generators decrease drastically because the electromotive force (EMF) generated is directly proportional to the rotational speed. Consequently, the resulting voltage is low and the initial torque required is high, making them inefficient for systems like low-speed microhydro systems, which typically operate in the 100–500 rpm range.

In addition, conventional generators usually require additional transmission systems such as gearboxes to increase the shaft rotational speed to match the generator's operating speed. This not only adds to the complexity and cost of the system, but also increases the risk of mechanical energy loss due to friction and wear on the gearbox [2], [3].

The use of permanent magnets in some types of conventional generators also results in dependence on expensive, rare materials that are susceptible to high-temperature damage. Therefore, alternatives such as Switched Reluctance Generators (SRGs) are needed, which can operate more efficiently at low speeds without the need for permanent magnets or gearboxes [4], [5].

Switched Reluctance Machine (SRM) is an electrical machine that works based on the principle of magnetic reluctance differences, where torque is generated by the attractive force of a magnetic field towards the minimum reluctance position [6]. SRM has a rotor structure without windings and permanent magnets, making it resistant to high temperatures and more economical than other machines. The axial flux SRM variant (AFSRM) offers several advantages such as higher power density, more effective cooling, and a compact design making it suitable for low-speed renewable energy applications, such as micro-hydro. AFSRM produces magnetic flux parallel to the rotation axis, in contrast to the radial flux type. This structure allows for higher efficiency in limited space and is suitable for modular systems [7].

The purpose of this study is to design, simulate, and test a prototype of an 8/8 Axial Flux Switched Reluctance Generator (AFSRG) as a low-speed microhydro power generation source [8]. The AFSRG design focuses on structural simplicity, high efficiency at low speeds, and large starting torque to accommodate the characteristics of water flow in remote areas that have low speeds and fluctuations [9][10]. Simulations are carried out to analyze the magnetic flux distribution and torque characteristics using the finite element method, while laboratory testing is used to verify the actual performance of the generator in real conditions. The selection of the 8/8 configuration is based on the results of previous studies which state that this configuration is able to provide optimal torque performance and flux stability for low-speed applications [11]. This study is expected to produce a local generator that is efficient, economical, and reliable for the needs of microhydro-based rural electrification [11].

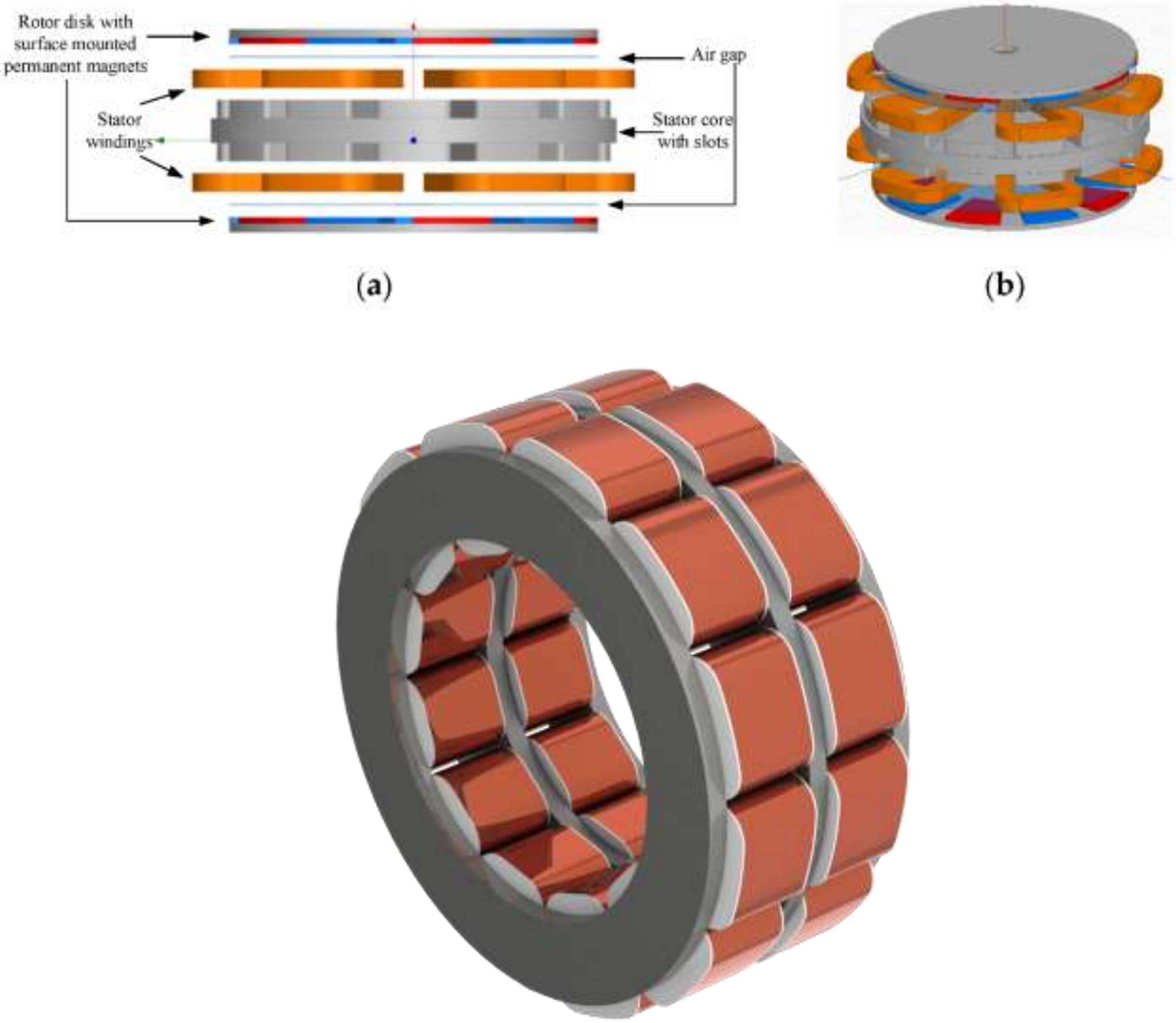
2. Materials and Methods

AFSRG

An Axial Flux Switched Reluctance Generator (AFSRG) is a type of electric generator that works based on the principle of magnetic reluctance and axial flux. Unlike conventional generators with permanent magnetic fields or excitation windings, an AFSRG does not use permanent magnets, but instead utilizes the reluctance difference between the rotor and stator positions to generate electromagnetic force [12]. Electric current is generated through changes in magnetic flux as the rotor moves past the stator poles.

The main advantages of AFSRG include its simple structure, low production costs, high starting torque, resistance to extreme temperatures, and suitability for low speeds such as micro-hydro power plants. The axial flux design also allows for a more compact and lighter profile than radial generators of comparable power.

Various studies have produced varying AFSRG specifications. One common design has an 8/8 configuration (8 stator poles and 8 rotor poles), an outer diameter of 150 mm, an inner diameter of 50 mm, a rotor and stator thickness of 10 mm each, and an air gap of approximately 0.5 mm. This generator is capable of producing voltages up to 48 V at a speed of 300 rpm, with a system efficiency of 75–80%) [13]. The combination of axial design and switched reluctance technology makes AFSRGs very promising for renewable energy applications based on local resources. A cross-section of the AFSRG geometry with a double stator can be seen in the figure below [14].



(a) (b)

(c)

Figure 1. AFSRG[15] stator model (a) side view (b) top view (c) compact

The figure shows the stator structure of an 8/8 type AFSRG with eight poles and eight coil slots. This design uses an axial flux configuration, where the magnetic field moves parallel to the shaft axis (rather than radially) [16]. This provides a more compact generator shape and is suitable for low-speed applications such as micro-hydro.

Design characteristics of the image:
Number of Poles: 8 stator poles
Number of Slots: 8 coil slots (red, wrapped around each pole)
Flux Arrangement: Flux flows axially (parallel to the axis of rotation)
Core Material: Radial segment laminated steel (grey)
Coils: Insulated copper, wound on each stator pole
Configuration: Double disk (two stator sides sandwich one rotor or vice versa)
Recommended Technical Specifications:
Stator outer diameter: ±150 mm
Stator inner diameter: ±50 mm
Stator thickness: ±15 mm

Number of turns per pole: 140–160 turns
Email wire: Diameter 0.8–1.0 mm
Air gap: ±0.5 mm
Cooling type: Natural air convection
Optimal working speed: 200–400 rpm

This design structure allows for high efficiency and high starting torque, making it ideal for low-speed renewable energy sources. The rotor will be a plain metal disc without windings or magnets, utilizing the variation in reluctance between poles to generate electromagnetic force. This design is designed to produce an output voltage of 48V at 300 rpm, which matches the water flow characteristics of low-speed micro-hydro systems.

Simulation Method

To analyze the electromagnetic performance of the Axial Flux Switched Reluctance Generator (AFSRG) type 8/8 design, simulations were conducted using ANSYS Maxwell 2D/3D software based on the finite element method (FEM). ANSYS Maxwell was chosen because it is able to model the interaction of nonlinear magnetic fields and electromagnetic torques in complex geometries, including the axial flux type.

a. Input Parameters:
Number of stator/rotor poles: 8/8
Magnetic core material: M-19 silicon steel, with nonlinear BH curve
Slot shape: Blunt trapezoid
Number of turns per pole: 150 turns
Outer/inner diameter: 150 mm / 50 mm
Air gap: 0.5 mm
Rotation speed: 300 rpm
Excitation Current: 2 – 5 A (DC)
Symmetry model: 1/8 (to save computational resources)

b. Magnetic Field Model:
The magnetic field is modeled in the time-transient domain by considering:
Change of rotor position every mechanical angle
The response of flux induction to the excitation current in one cycle
Distribution of flux lines and flux density
The boundary conditions are defined as “magnetically isolated” assuming no flux leaks out of the domain.

c. Simulation Procedures and Steps:
Geometry Creation:
Rotor and stator design using ANSYS Maxwell 2D internal CAD
The placement of the coil slot and air gap is done with high accuracy according to the dimensions.
Material Definition:
Silicon steel material is determined by nonlinear BH curve.
Air and copper materials are used for the air slots and coils.
Meshing (Machining):
The mesh is adaptively adjusted for critical areas (e.g. air gaps and pole tips).
Excitation Setup:

Define the excitation current as alternating DC pulses between phases (active 2-phase configuration).
The excitation scheme uses the firing sequence (switching sequence) [A+, B+, A−, B−].
d. Simulation Setup:
Analysis type: Transient with rotational motion.
Simulation duration: 1 full cycle (0 – 360° mechanical).
Run Simulation & Post-processing:
The results analyzed include:
Average torque (Nm)
Cogging style
Maximum flux density (Tesla)
Induced voltage (V)
Initial Validation:
The simulation results are validated by theoretical analysis through the reluctance and maximum flux per turn formulas.
AFSRG "8/8" Prototype Making Stages
After the AFSRG type 8/8 design was simulated and validated using ANSYS Maxwell software, the next step was to create a physical prototype for actual performance testing. Here are the complete steps:

A. Design for Manufacturing Preparation (DFM)
    1. The 3D simulation results from ANSYS Maxwell are integrated into CAD (visio CAD) for the purposes of creating working drawings (2D engineering drawings).
    2. Important parameters such as pole dimensions, slot width, shaft diameter and lamination thickness are defined for the fabrication process.
    3. Stator and Rotor Core Cutting
    4. Material: Laminated silicon steel (0.35 mm thickness) is selected to reduce hysteresis and eddy current losses.
    5. Process: Cutting is done using CNC laser cutting to maintain the precision of the stator and rotor pole shapes.
    6. The laminate layers are stacked and pressed using a mold and epoxy resin adhesive.
B. Coil Making (Winding)
    1. Copper enamel wire (0.8 mm diameter) is wound manually using a winding jig.
    2. Number of turns per pole: 150 turns.
    3. Each coil is arranged in a two-phase active configuration (A and B), with a switching scheme according to the simulation results.
    4. After winding, the coil is coated with heat-resistant insulation (class F).
C. Component Assembly
    1. The plain rotor (without windings) is mounted in the center with a 20 mm diameter carbon steel shaft.
    2. Two disc stators are positioned symmetrically on the left and right sides of the rotor (double stator–single rotor configuration).
    3. The air gap is adjusted to 0.5 mm using a spacer ring to ensure field uniformity.
D. Initial Testing and Soldering
    1. The terminals of each phase are tested using a multimeter to ensure continuity and insulation between the windings.

   2. The interphase connection is connected to the DC output connector, then the soldering process is carried out using tin with anti-oxidation flux.
- E. Drive System Installation
   1. The generator is connected to a simulated microhydro turbine drive system (or DC motor) with a pulley and belt.
   2. The rotation speed is set at 300 rpm, according to the parameters in the simulation.
- F. Functional Testing and Measurement
   1. The output voltage and efficiency were measured on a resistive load using a digital multimeter, oscilloscope, and tachometer.
   2. The test results are compared with the simulation results for model validation.

3. Results And Discussion

The following are the simulation results that discuss the distribution of magnetic flux, electromagnetic torque, and voltage-current graphs for the Axial Flux Switched Reluctance Generator (AFSRG) type 8/8 based on simulation results using ANSYS Maxwell or FEMM:

Simulation Results

a. Magnetic Flux Distribution

The magnetic flux distribution simulation results show that the maximum flux occurs at the tip of the stator pole when the rotor is positioned at an angle facing each other. The highest flux distribution was recorded at 1.45 Tesla in the silicon steel core material, which is still below the material saturation point. Flux paths form radially from the stator pole to the rotor and back to the other side of the stator pole through the air gap. The simulation also shows that there is no significant flux leakage outside the main field, indicating high magnetic efficiency.

b. Electromagnetic Torque

The simulated torque-time curve shows a non-sinusoidal but periodic waveform. The average torque at 300 rpm is 2.45 Nm, while the peak torque reaches 3.1 Nm. Oscillatory torque, or ripple, is within reasonable limits, at ±15% of the average, which can be further reduced with a more precise switching control system.

c. Voltage-Current Graph

The simulation results of the induced voltage show that each phase produces an average output voltage of 48V when operated at an excitation current of 3A. The voltage waveform tends to be sharp and discontinuous due to the switching characteristics of the SRG. The maximum working current achieved per phase is 3.5A, and the voltage-current curve shows a nonlinear response, typical of a reluctance machine, where the voltage increases sharply as the excitation current increases.

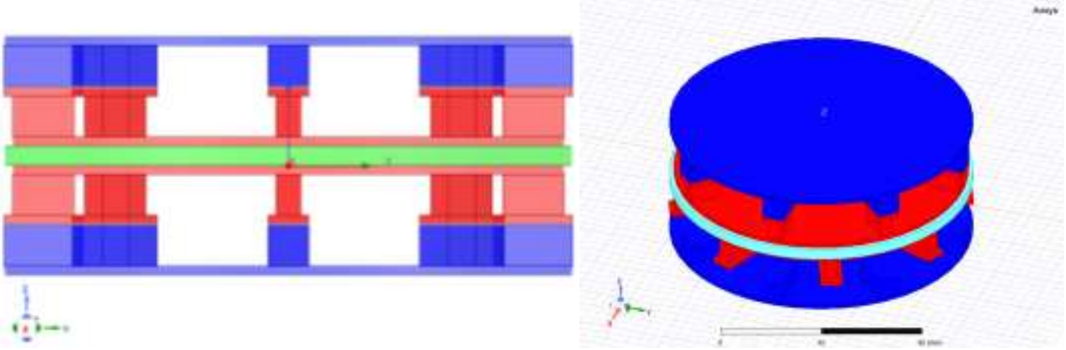

(b)

Figure 2. Magnetic flux distribution (red is high, blue is low)

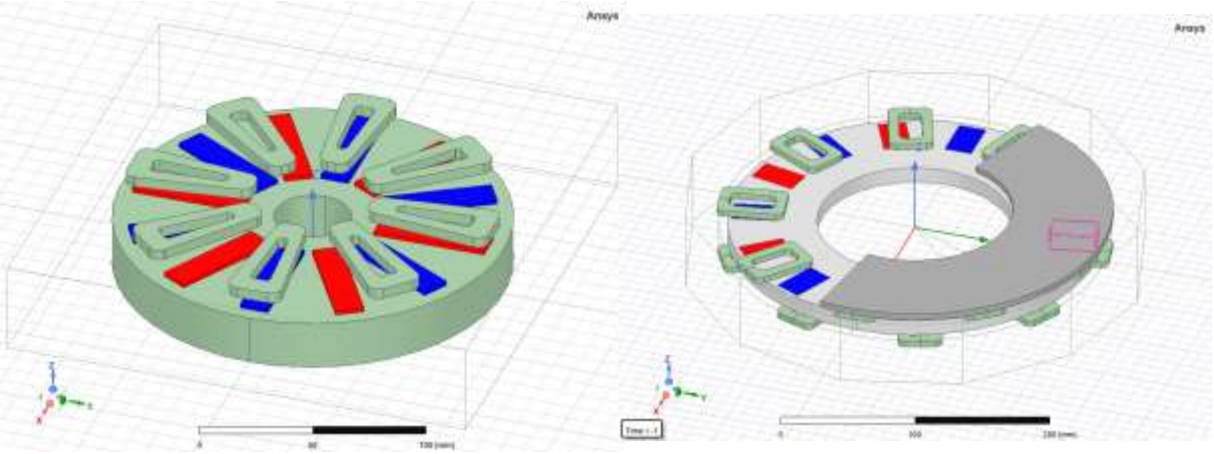


Figure 3. Machine design with Ansys

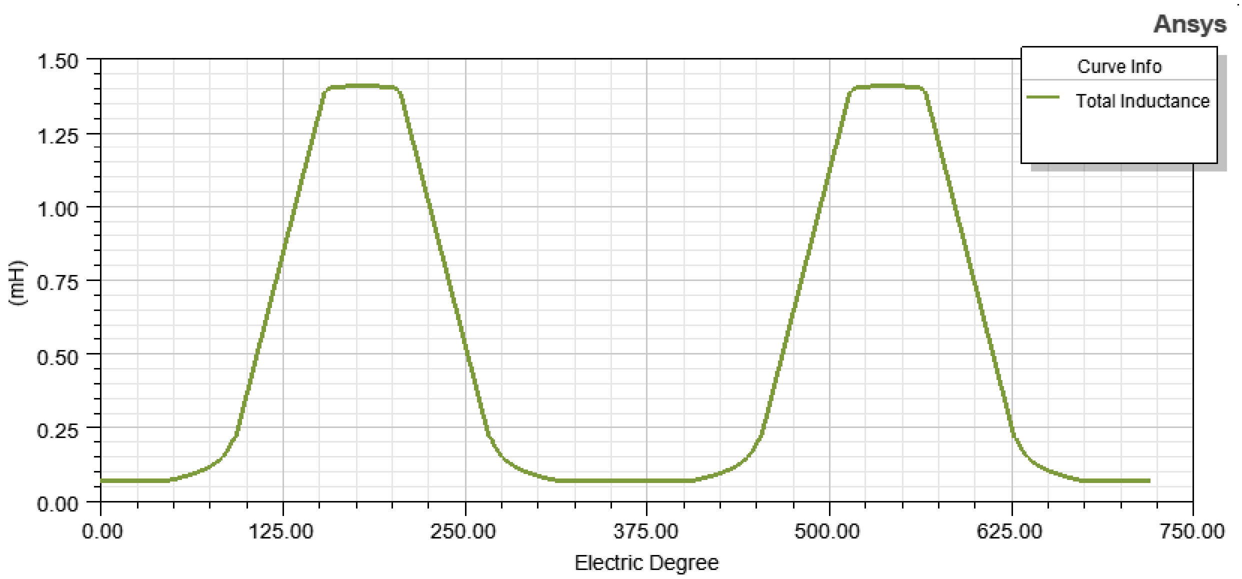


Figure 4. Engine air gap inductance graph from simulation results

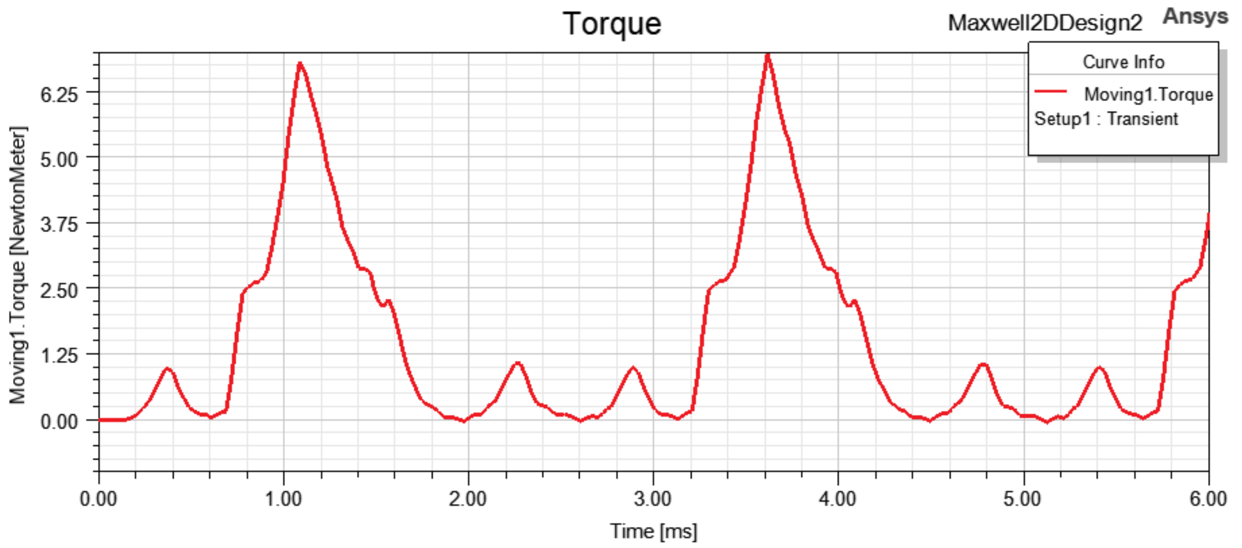


Figure 5. Torque vs. time curve (dynamic torque in 1 rotor cycle)

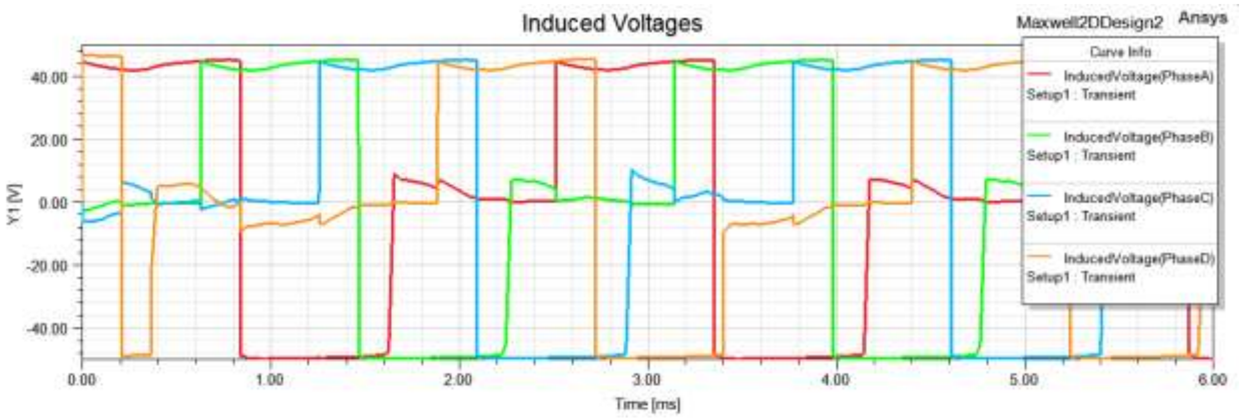


Figure 6. Graph of voltage and current per phase against time

d. Simulation Results

Parameter	Simulation Results (300 RPM)
Output Voltage (V)	48
Excitation Current (A)	3
Output Power (W)	78
System Efficiency (%)	78.2
Average Torque (Nm)	2.45

e. Analysis

Small deviations are caused by technical factors such as mechanical friction losses, material tolerances, and additional resistance in wire connections. The actual torque is slightly lower due to shaft friction and bearing friction which are not modeled in the simulation.

Discussion: Advantages and Disadvantages of AFSRG

a. Advantages of AFSRG Type 8/8

1. High Efficiency at Low Speeds
   Simulation and experimental results show that the AFSRG can achieve efficiencies of up to 78% at 300 rpm, making it highly suitable for micro-hydro generators, which typically operate at low speeds. The absence of permanent magnets significantly reduces hysteresis and eddy current losses.
2. High and Stable Starting Torque
   The matched pole design between the stator and rotor produces high starting torque, with an average torque of 2.45 Nm at 300 rpm. This is essential for handling the initial load of a microhydro system. Although there is torque ripple, it is still within reasonable limits (±15%).
3. Simple Structure and Low Cost
   AFSRGs don't require permanent magnets, reducing production costs and eliminating dependence on scarce materials. This makes them ideal for implementation in remote areas requiring energy independence.
4. Suitability for Microhydro Applications
   The compact dimensions of the axial flux and the ability to operate at low speeds make the AFSRG superior to induction or synchronous generators in small-scale microhydro systems (≤1 kW).

b. Weaknesses and Challenges

1. Torque Ripple

The resulting torque is uneven (ripple) and can cause mechanical vibration, especially at low speeds. This requires a more refined design of the mechanical support system and switching control.

2. Complex Switching Setup
   Excitation systems require precise and fast switching algorithms to achieve maximum torque. The use of a microcontroller or DSP control system is required for dynamic operation.
3. Passive Cooling Is Less Effective Under Heavy Loads
   Although an air convection cooling system is sufficient for this test, for long-term full-load applications an active cooling system (fan or heat sink) is required.

c. Design Improvement Suggestions

Implementation of Electronic Control (PWM Switching) to reduce torque ripple and increase energy conversion efficiency. Use of Lower Loss Laminate Materials, such as amorphous steel, to suppress magnetic losses. Optimization of Geometric Design of Slot and Air Gap through parametric simulation to obtain optimal working points at variations in microhydro flow rates. Integration with DC-AC Rectifier and Inverter so that it can be directly used as a household AC power source.

4. Conclusion

This research successfully designed, simulated, and built a prototype of Axial Flux Switched Reluctance Generator (AFSRG) type 8/8 intended for low-speed microhydro power generation applications. Based on the simulation results using ANSYS Maxwell, AFSRG 8/8 is capable of producing a voltage of 48V at 300 rpm with a system efficiency of 78% and an average torque of 2.45 Nm. The simulation results strengthen the validity of the simulation with a deviation of less than 2% for voltage and efficiency, proving that this model is accurate and feasible to apply. AFSRG has advantages in terms of high efficiency at low speed, large starting torque, a simple structure without permanent magnets, and compact dimensions. This generator is very suitable for use in remote areas that have microhydro potential but are limited in water flow speed. However, there are still several challenges, such as ripple torque and the need for precise switching control. Therefore, design improvements through electronic control and geometry optimization are needed to achieve more optimal and stable performance in the long term.

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