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The Effect Of Stator Excitation Current On The Driving Torque Of A Single-Phase "6/6" Switched Reluctance Generator Design With External Excitation

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ABSTRACT
Generator Reluktansi Berpindah (SRG) telah menarik perhatian karena konstruksi yang kokoh, biaya rendah, dan toleransi kesalahan yang tinggi, sehingga cocok untuk lingkungan ekstrem. Namun, SRG mengalami fluktuasi torsi dan kebisingan akustik akibat hubungan non-linier antara torsi dan arus eksitasi. Meskipun optimasi komponen SRG telah diteliti, masih ada celah dalam analisis pengaruh arus eksitasi stator terhadap torsi penggerak pada desain SRG fase tunggal "6/6" dengan amplifikasi eksternal. Studi ini menganalisis dampak variasi arus eksitasi stator terhadap torsi penggerak SRG fase tunggal 6/6. Metodologi meliputi desain, analisis elemen hingga (FEA), dan pengujian prototipe torsi penggerak awal. Hasil menunjukkan bahwa peningkatan tegangan suplai kumparan stator menghasilkan gaya magnetik yang lebih besar, yang menyeimbangkan torsi mekanik pada poros rotor. Pemahaman ini sangat penting untuk mengoptimalkan kinerja torsi, mengurangi riak, dan meningkatkan efisiensi SRG untuk aplikasi di masa depan.

ABSTRACT
Switched Reluctance Generators (SRGs) have attracted attention due to their robust construction, low cost, and high fault tolerance, suitable for extreme environments. However, SRGs suffer from torque ripple and acoustic noise due to the non-linear torque-excitation current relationship. Although SRG component optimization has been investigated, a gap exists in the analysis of the effect of stator excitation current on the drive torque in a single-phase "6/6" SRG design with external amplification. This study analyzes the impact of varying stator excitation current on the drive torque of a single-phase 6/6 SRG. The methodology includes design, finite element analysis (FEA), and testing of an initial drive torque prototype. Results show that increasing the stator coil supply voltage results in a greater magnetic force, which counteracts the mechanical torque on the rotor shaft. This understanding is crucial for optimizing torque performance, mitigating ripple, and improving SRG efficiency for future applications.

INTRODUCTION

Switched Reluctance Generator (SRG) is one type of electric machine that is increasingly attracting attention in various modern applications. Unlike conventional generators, SRGs have a toothed stator and rotor structure without any permanent magnets or windings on the rotors. Its working principle is based on the tendency of magnetic circuits to adopt a minimum reluctance configuration, where electromagnetic torque is generated when the rotor poles are aligned with the stator poles at the maximum inductance of the excited stator windings [1]. Thanks to its unique characteristics, SRG is widely used in critical applications such as starter/generator systems for aviation, electric or hybrid vehicle drive systems, and wind or wave power generation systems in the low to medium speed range. In high-speed applications such as steam and gas turbines, SRGs even allow the removal of gearboxes in electric power systems, which can simplify design and reduce maintenance costs [2].

Table 1. presents a concise comparison between Switched Reluctance Generators (SRGs) and conventional generator types, highlighting their advantages and characteristics that are relevant to the context of this study.

Table 1: Comparison of the Advantages and Disadvantages of SRG with Conventional Generators

Comparison Criteria	Switched Reluctance Generator (SRG)	Permanent Magnet Synchronous Motor (PMSM) / Generator[3]	Induction Motor (IM)/Generator[4]
Construction	Simple, sturdy, no winding/magnet rotor	Complex, using permanent magnets	Relatively simple, rotor windings
Manufacturing Costs	Low	High (due to permanent magnets)	Low to medium
Fault Tolerance	Height (independent phase)	Low (magnetic demagnetization, phase dependence)	Intermediate
Magnet Requirements	None	Yes, permanent magnets	None
Torque Ripple	High (inherently, need control)	Low (with good control)	Intermediate
Acoustic Noise	Significant (torsional ripple-related)	Low	Intermediate
Power Density	Tends to be low	Tall	Intermediate
Extreme Environmental Operations	Excellent (high temperature/pressure)	Limited (magnets are heat sensitive)	Good

Although there has been a lot of research focused on optimizing individual components of SRGs, such as structures, controls, and power electronics devices, the comprehensive performance of SRGs as a whole has not been widely publicized. This suggests there is a gap in a holistic understanding of how different aspects of SRG interact to produce total performance. Research on the effect of stator excitation currents on drive torque has been conducted, often to optimize the excitation waveform to minimize RMS currents for a specific average torque or eliminate torsional ripples [5]. However, most of these studies focus on Switched Reluctance Motors (SRMs) or generators in general. There is a clear gap in the comprehensive and specific analysis of how the excitation current of the stator affects the driving torque of the design.

The gap in the core research does not lie in the general understanding of SRG or its excitation, but rather in a comprehensive analysis of a specific practical configuration, i.e. a single-phase "6/6" SRG with external amplification, regarding the precise effect of the excitation current of the stator on its driving torque. This research is very important because it directly aims to understand and optimize the effect of the excitation current of the stator on the driving torque [6]. Thus, this research can provide a basis for the mitigation of high-torque ripples and acoustic noise, which are the main drawbacks of SRGs that hinder its widespread adoption. A deeper understanding of these relationships will allow the development of more sophisticated control strategies, which in turn can improve the efficiency, power density, and overall reliability of a 6/6 phase SRG with external amplification. This optimization is crucial to make SRG more competitive and commercially viable for practical applications.

This research will contribute to the development of a more accurate modeling framework for this specific SRG configuration, allowing for better performance prediction prior to prototype implementation, thereby saving development time and costs. This study aims to analyze and characterize in depth the effect of stator excitation current variations on the drive torque generated by the design of a single-phase "6/6" Switched Reluctance Generator with external amplification. Focus will be on identifying the non-linear relationship between excitation current and torque, optimization of excitation parameters to achieve optimal torque performance, as well as the potential for torque ripple mitigation inherent in this machine.

METHODS

Main material

In the design of radial SRGs and prototyping are:

1. Design results with drawing Viso software
2. Core materail in the form of carbon steel plate plates
3. Copper conductor with email insulation
4. 12 mm, 10 mm, and 5 mm bolts/screws.
5. 0.1 mm nomex roll insulation paper
6. Core rod size 32 mm in diameter
7. Bearing hole diameter 32 mm
8. Iron housing
9. 1 hp drive motor
10. PVC insulated coated copper fiber cable
11. The testing materials are in the form of:
12. Power supply 0-15 Volt
13. Digital multimeter with clamp
14. Mechanical torque gauge

From the basic materials used, a design and prototype of the results will be used in this study.

Classic size approach:

Classical measurement approach: in this study to design the model used the classical measurement approach to see how important it is to consider advantages in the early stages of engine design. The classic approach is that the basic model approach of all electric machines is radial with stators and rotors in layers. The first step in machine design is to roughly estimate the size of the main components. It is well known [7], [8] that the main electromagnetic size equation for electric machines is related to torque. Therefore, this chapter will concentrate on the classical electromagnetic size of a cylindrical electric machine and how it impacts torque. The magnetic field energy present in the air gap of the engine can be used to determine the relationship between the general torque and the general cylinder engine. Cu Utilization Coefficient is one common approach to attributing engine dimensions to specifications [8].

With the size approach, a design was made that is in accordance with the basic theory of *switched reluctance machine*, namely with a stator that has windings and a rotor consisting of an arrangement of carbon steel plates shaped to resemble poles protruding outwards like gears. The design can be seen in Figure 1.

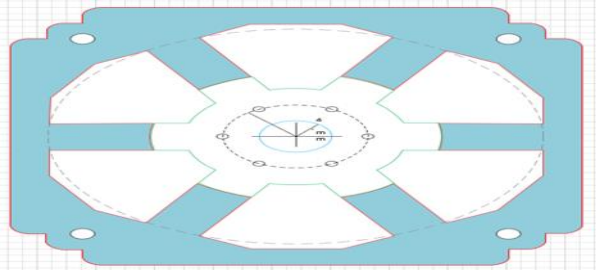

Figure 1. Sketch the shape of the SRG design.

Equations used for FEA:

A set of equations explaining the problem is given below. The density of magnetic flux B in magnetic materials can be given as [32].

$B = \mu H = \frac{H}{\gamma}$ (1)

where is the density of the magnetic field, μ is the permeability of the magnetic material, and γ is the rreachability of the magnetic material. From Ampere's law,

$curl\ (B) = \mu J_0$ (2)

where is the current density J_0

Define magnetic vector potential as,
$B = curl(A)$
$curl\ (curl(A)) = \mu J_0$

Setting ,and from the vector identity to curl from curl vector curl$\nabla . A = 0$

$\nabla(\nabla . A) - \nabla^2 A = \mu J_0$ (3)
This implies that,
$\nabla^2 A = -\mu J_0$
Using Assumption() obtained below the drop, the above expression can be written as,$\nabla = \frac{\partial}{\partial x}\frac{\partial A}{\partial y}$
$\frac{\partial}{\partial x}\frac{\partial A}{\partial x} + \frac{\partial}{\partial y}\frac{\partial A}{\partial y} = -\mu J_0$ (4)
Equation solution (3) gives the magnetic vector potential A inside the motor. This potential is obtained by using interpolation techniques to minimize the function of online energy.

$F = \int_Q \left[\int_0^B H . dB - \int_0^A J_0 . dA\right] dQ$ (5)

Where Q is the integration completion area. The entire settlement area of Q is subdivided into triangular finite elements. The elements are defined in such a way that the sides of the triangle coincide with the boundary of each material. FEMM implements this by allowing the placement of nodes at each boundary. The following assumptions are made to estimate the magnetic field within the SRM [9]: The outer surface of the stator is treated as a potential line of zero magnetic vector. The nodes along this flux are defined using the Dirichlet boundary conditions. All formulas are used in computer programs so that the calculations and design results are close to the values that correspond to the actual situation.

1. The magnetic material of the stator and rotor is isotropic
2. The magnetic vector potential and current density only have z-directed components.
3. The stator winds are identical and are positioned symmetrically along the stator holes.

4. The stator and rotor are concentric, and the air gap separating them has a constant width at an aligned position.
5. End effects, hysteresis effects, and skin effects are negligible

The SRG design specification is 6/6 single-phase, 1 kW, 1000 rpm. To meet the electrical output of 1 kW, the base model is determined taking into account the rated torque and rated speed. Once the design specifications are determined, the design is carried out according to the design process illustrated in Figure 2.

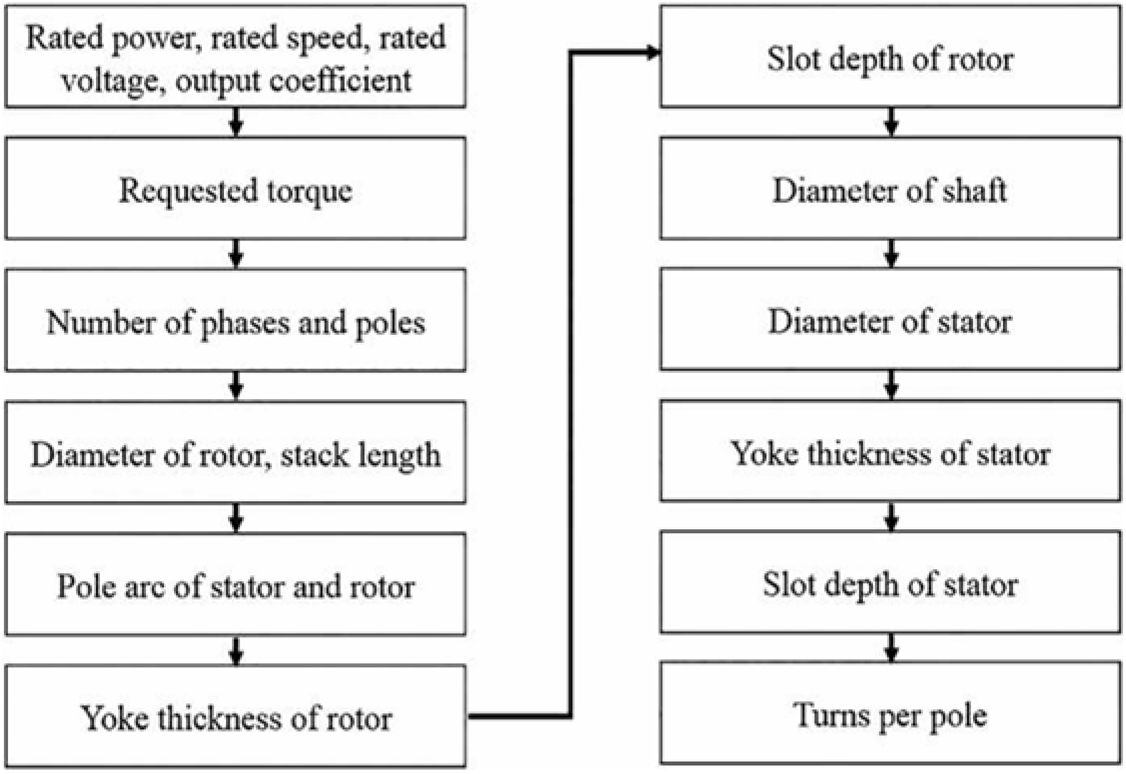

Figure 2. SRG planning diagram[10], [11]

Prototype design is achieved in three stages:
1. The size of the machine taking into account the requirements.
2. Design evaluation using magnetic analysis with finite element method.
3. Thermal characterization of the prototype being built.

Selection of number of phases:

Since a single-phase engine cannot be started if the rotor and stator are aligned[12] when the SRM is designed to operate in motor mode, there are many considerations to consider when selecting the number of phases. However, when SRM operates in generator mode, these considerations can be ignored and the generator is designed with a single phase (Np = 1) to obtain generation behavior with only one part of the capacitor parallel to this phase.

Selection of the number of poles:

In a single-phase machine, the number of rotor and stator poles is the same, Ns = Nr. The maximum speed of the machine is related to the number of poles, or the frequency of the rotor and the application of the machine. The high production cost is due to the larger number of poles as there are more coils. With the general speed of the wind turbine of 1 kW and the oscillating frequency of the resulting circuit, a six-pole design (Ns = Nr = 6) has been chosen for the rotor and stator. The behavior of this machine indicates the AC cycle every two gears; as a result, when a rotor with Nr = 6 rotates at 1000 rpm, an electrical frequency of 50 Hz is obtained. After that, the next step is to identify each of the dimensions of the machine.

Diameter and length of the pile[12].

Based on a rated power of 1 kW, the design of the switch reluctantance generator is based on the relationship between torque, power, and speed, the external volumetric limitations for the size of the nest to be placed in the generator (250 x 250 x 60 mm), and the fact that the torque is proportional to the volume of the rotor as shown (6) [13]. The tangential force density on the rotor surface of 3.81·104 N/m2 determines the proportionality constant. Ansys© is used to implement a design that provides a sequenced procedure for calculating values for each rotor and stator dimensions.

$T \propto k.{D_2}^2 \cdot Ls$ (6)

The length of the generator, Ls, is defined as the multiple or subfold of the diameter of the rotor hole [12] given by equation (7). With , obtained . The rotor diameter is selected according to the external dimensions, taking into account that the machine can be installed inside its nest.$k = 0{,}5T \propto \pi \cdot (D/2)^3$

$Ls = k \cdot D$ (7)

Thus, the value of the rotor diameter is D = 120 mm, and using (7) the length of the pile is . In this study, to save costs, a degradation factor of 30% was set, the stack length can be taken 42 mm. But this will affect the output power of the generator, including torque.$Ls = 60\ mm$. Without interfering with the production molding process, air gaps can be minimized. But this will be very difficult if we do printing with a laser cutting machine, because the cut that leaves the residue is not 100% even.

Rotor and stator polar distance:

The angle of the pole () is the angle between the two poles of a rotor or statorα_{k-k}[12]. This is determined by equation (3), equal to the number of rotor poles as well as the stator, so that . The standard value of the air gap for this size machine is . The diameter of the hole or stator is (), so that .$N_x Ds = 120{,}6\ mm l_g = 1\ mm Ds = D + 2l_g\ 118{,}6 + 2.1 = 120{,}6\ mm Ds = 120{,}6\ mm$

$\alpha_{k-k} = \frac{2\pi}{N_r}$ (8)

$P_{pitch} = \alpha_{k-k} \cdot \frac{D_x}{2}$ (9)

The flux value of each phase is very different. In an unaligned position, the ends of the poles are separated by 20.. The width of the rotor pole is wider than the stator pole, so there is more air gap than the width of the stator pole. The calculation for this uses the press. (10) and the pole width of the press rotor. (11).l_g

$t_s = \frac{2\pi(D_s/2)}{2N_r} - 21l_g$ (10)

$t_r = t_s + 2.l_g$ (11)

Rotation per coil and its resistance:

The rotational speed is estimated to be rpm, so,$\omega = 500$

$f = \frac{500\ rpm}{60\ detik} \times 6\ kutub = 50\ Hz$

with an electrical frequency Hz. Equal to the measured power of 1 kW and an efficiency of 0.8, the energy per cycle is calculated by (12), and the value is obtained as 25 Joules.$fs = 50 P \eta E_{1\ putaran}$

$$E_{1\ putaran} = \frac{P/\eta}{f_s} \quad (12)$$

$$E_{1\ putaran} = \frac{1000/0{,}8}{50} = 25\ Joule$$

In terms of flux and current, the energy per revolution is provided by (8)

$$E_{1\ putaran} = 2.\lambda_{max}.i_{max}.K_{ap} \quad (13)$$

where is the ratio between the area of the rectangle that borders the leaf in Figure 1 and the leaf-shaped area itself. When the machine is operating in a stable state, the variable has a positive semicycle, as shown in Figure 3. Since the rectangle of the boundary corresponds to the maximum connected flux and the maximum phase current, it indicates the size of the machine. The results of the FEM simulation show that the maximum amplitude of the current, and the maximum amplitude of the flux are connected, which is set by (14) with $K_{ap}\lambda - iKap = 0{,}5 i_{max}, \lambda_{max} S = Ls(Ppitch - ts)$.

$$\lambda_{max} = N.B_{max}.S.N_s \quad (14)$$

It should be noted that the maximum current and flux are not the same thing. From (13) and (14) we obtain the number of winds per coil N required by the specification. The energy produced is seen in Figure 3. The coil is designed with a rectangular cross-section. The diameter of the wire is 0.8 mm. Each coil has 220 coils of two copper

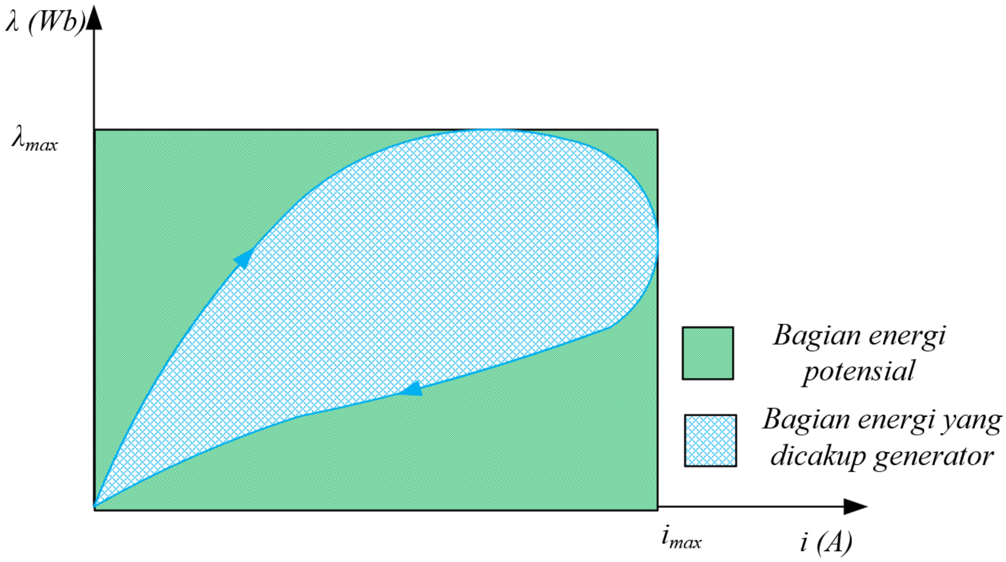

Figure 3. Energy magnetization generator

The prototype was made using a stator coil with an aluminum-alloy copper conductor with a diameter of 0.8 mm. The number of windings made is 220 windings. The circumference height is 50 mm with a thickness of 20 mm.

RESULTS AND DISCUSSION

From the initial explanation for designing an SRG machine, the magnitude of the design results is obtained as follows in Figure 4:

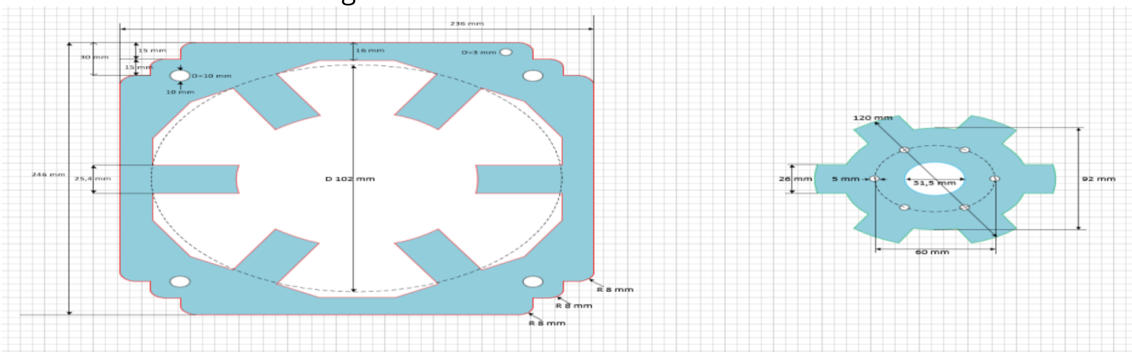

Figure 4. 2D design of SRG "6/6"

The parameters of the design are then transferred in the mold program for CNC machining. The resulting prints are assembled according to the basic model of a machine that will be tested. The results of the basic prototype of the engine in this study can be seen in Figure 5.

Figure 5. SRG Prototype

In this study, after a prototype was made, a test was carried out. In this study, the test was only carried out for the starting drive torque to rotate the generator shaft. This experiment was carried out because to produce the output power of the generator, a suitable starting drive is required. Therefore, in this study, only the starting torque is required. The torque test series is as shown in Figure 6.

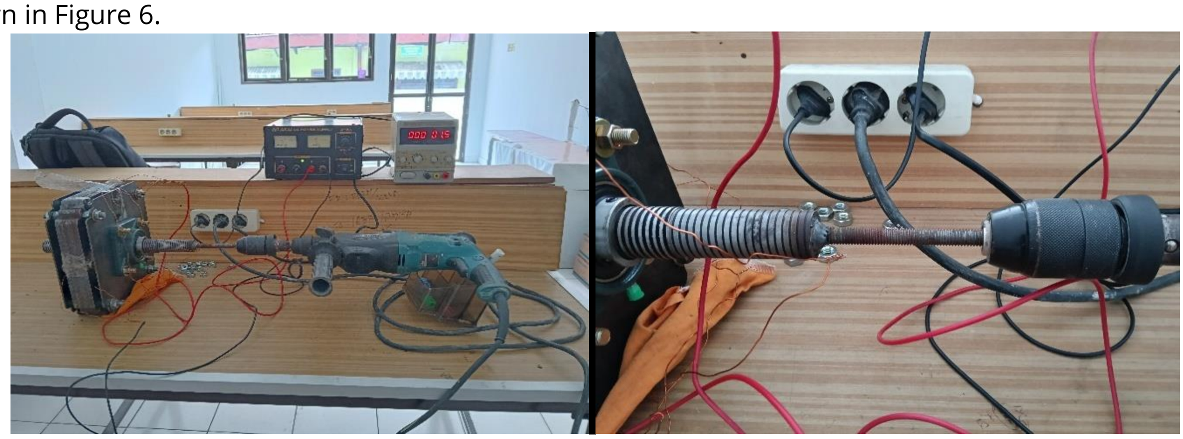

Figure 6. Testing network

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Figure 7. Power supply DC coil

Table 1. Generator drive torque measurement results

Percobaan	Tegangan	Nilai torsi			
	(V)	(N.m)	Kgf.m	Lb.ft	Lbf.Inch
1	11	20	1	15	200
2	14	24,5	2,2	17,4	220
3	15	26	2,5	20	240

By interpolating from Table 2 data, a graph showing the relationship between the supply voltage of the stator coil and the torque it produces is shown in the graph in Figure 8.

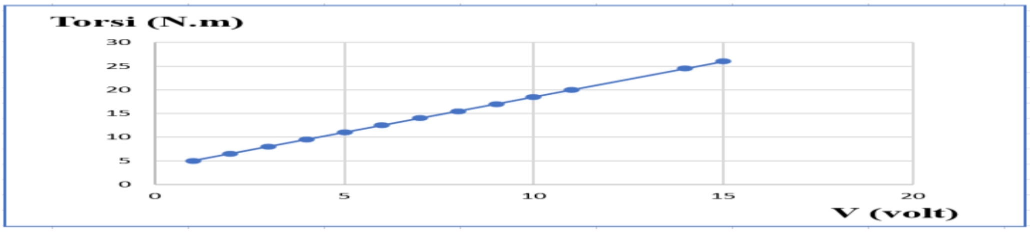

Figure 8. Rotor shaft torque graph

The voltage supplied to the stator coil will generate a magnetic field and attract the nearest rotor pole. The resulting force must be counteracted by the mechanical rotating force on the rotor shaft. This torque will generate the output voltage at the generator terminals and the connected load current. However, it is important to create a control suite in order to generate more power.

CONCLUSIONS AND SUGGESTIONS

Conclusion

This study successfully analyzed the effect of the excitation current of the stator on the driving torque in the design of a single-phase "6/6" Switched Reluctance Generator (SRG) with external amplification. Although SRGs offer advantages such as rugged construction and low cost, inherent challenges such as torsional ripples and acoustic noise due to the non-linear nature of torque-excitation currents are still a concern. Using the classical sizing approach, finite element analysis (FEA), and prototype testing, the study showed that an increase in the supply voltage of the stator coil directly resulted in a greater magnetic force, which must then be counteracted by the mechanical torque on the rotor shaft. A deep understanding of these relationships is crucial for identifying non-linear characteristics and optimizing excitation parameters. These results provide an important basis for torque ripple mitigation, improved efficiency, and reliability of SRGs, making them more competitive for future renewable energy applications.

Suggestion

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