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Research on optimal design of surface permanent magnet synchronous generator

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ABSTRACT

The more fossil energy is used, the less this energy source will become because it is not an infinite energy and it pollutes the environment, so there is a need for solutions with new and infinite energy sources such as wind energy. This paper designs and focuses on optimizing a floating magnet synchronous generator (SG) for a wind power generation system using finite element analysis (FEA) with ANSYS Maxwell software. This generator is compared with other types of generators such as squirrel cage induction generator (SCIG), wound rotor induction generator (WRIG), SG, doubly-fed induction generator (DFIG), and switched reluctance generator (SRG). Throughout the analysis and design process, the paper emphasizes the significant benefits of surface-mounted permanent magnet (SPM) motors in increasing efficiency and reliability while reducing supply costs. The research results of the paper aim to demonstrate that SPM can meet the needs of high efficiency and low cost in the industrial and civil fields. The results of this study by the authors will provide new contributions to serve as a basis for the design, manufacture, calculation and control of Halbach permanent magnet (Halbach PM) electric machines based on optimization techniques such as genetic algorithms (artificial intelligence) and sustainable optimization (for electrical equipment).

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1. INTRODUCTION

Nowadays, the automation control of some intelligent electric drive systems of industrial machines is industrialization and modernization have been and are being required and require the use of renewable energy sources in the future [1]-[6]. In the first quarter of 2021 of Vietnam electricity (EVN), the demand for electricity increased by 7.93%, according to documents [2]. However, energy sources from thermal power and hydropower are not enough to meet the load demand. Besides it also has a negative impact on the environment, so the development of renewable energy sources is the main answer to this and this energy can be concentrated for exploitation in the future. This is a sustainable energy source and can replace hydropower and thermal power in the future, which is always maintained and needs to be developed in wind energy, requiring accompanying power electronics to receive power, thereby having cost and reliability [4]-[6]. Floating magnet synchronous generator (SG) are showing benefits such as the ability to promote in design for application in renewable energy [7]-[11]. In Vietnam, a country that is developing at a high speed, the demand for energy is also increasing. With the limitations of energy sources such as the increasing price of oil and coal and this energy source will gradually become scarce in the future, promoting the search and development of alternative energy sources is necessary. With the benefits of wind energy in Vietnam is very large with a coastline of more than 3,000 km.

Research projects aim to integrate with the conversion devices to generate wind energy with performance and economic requirements. The best way is to optimize those requirements by giving simulation studies for manufacturers to evaluate the characteristics of the generator. Papers [2]-[4] design and optimize SG to give characteristics of current, voltage, torque, efficiency, and power but have not considered the influence of the Halbach magnet arrangement and have not compared with other types of machines. Finally, the design and optimization of floating magnet synchronous generators (SPM) will give characteristics such as current, voltage, torque, power, and efficiency. Besides, document [3] has designed but not compared with surface-mounted permanent magnet (SPM) generators using Halbach magnets.

Generators used for wind turbine systems differ from other conventional generators as follows, [5]: for the squirrel cage induction generator (SCIG): the squirrel cage rotor generator has high durability but low efficiency and is difficult to control [10]. The wound rotor induction generator (WRIG): has better controllability than the SCIG but is more complex in design [11]. For the synchronous generator (SG): often require complex excitation systems and may not be effective for applications with continuously varying power [12]. For the doubly-fed induction generator (DFIG): has high efficiency and flexible control but is expensive [13]. As for the switched reluctance generator (SRG): has a simple structure and high durability but creates a lot of magnetic noise and vibration [14]-[19].

From that we can see that the SPM generator has outstanding advantages such as [7], [20]-[26]: the ability to generate high power density and high efficiency at low wind speeds, can achieve better electrical transmission efficiency than other conventional generators and minimize mechanical damage. Simple structure and easy to manufacture. Specially designed with a simple permanent magnet structure that is easy to manufacture, helping to reduce the size and weight of the generator, making it easy to install and transport in places with difficult traffic [18], [23], [25], [26]. High reliability and low maintenance. With fewer moving parts than other previous wind generators. Reduce the size and weight of the generator, ensuring continuous operation for a long time.

2. RESEARCH CONTENT ON CALCULATING AND DESIGNING ELECTRICAL MACHINES

2.1. Theoretical foundations

Vietnam has a mountainous terrain in the west and gradually lowers towards the east, so it has a steep terrain, a long coastline and many islands. Therefore, the construction of wind turbine systems offshore and on land is feasible. Moreover, Vietnam is located near the equator, so the dry climate exists, so the wind is stable in the Central Coast of Vietnam. The wind turbine generators are designed with rotors attached to fans as shown in Figure 1 to convert wind energy from kinetic energy into mechanical energy on the turbine shaft connected to gearboxes or not. Depending on the wind speed, we can choose the appropriate for wind turbine. Wind turbine systems like Figure 2.

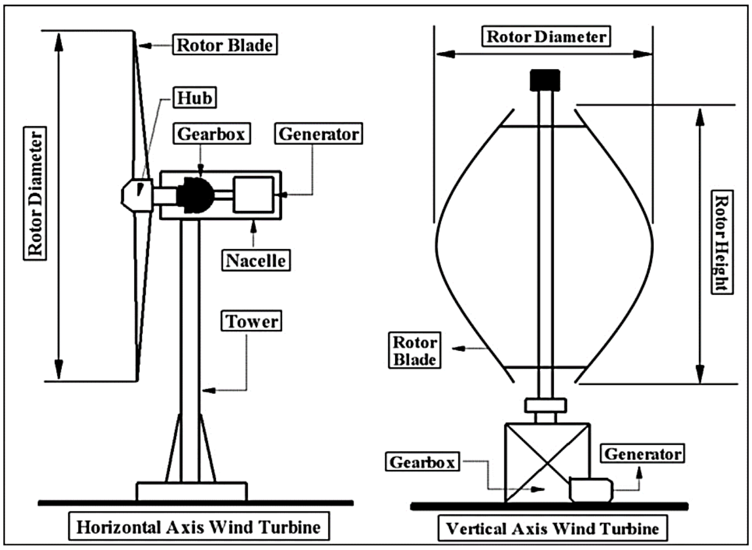

Figure 1. Some wind turbine type used popular

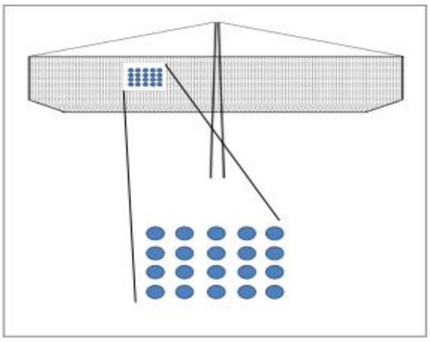

Figure 2. Turbine characteristic systems map

With power of wind turbine; number of blade Z=3 follow [1]-[4]. Air velocity $\mathrm{v} = 2\ \mathrm{m/s}$ to $\mathrm{v} = 8\ \mathrm{m/s}$. Wind turbine power is (1) [4], [6]:

$$P = 0.5.\rho.A.V^3 \tag{1}$$

Tip speed ratio is (2):

$$\lambda = \omega\frac{R}{V} \tag{2}$$

Inner rotor and length of rotor (3) [1]:

$$D = 3\sqrt{\frac{2p_1}{\pi\lambda} * \frac{p_1}{f_1} * \frac{S_{gap}}{C_0}} \tag{3}$$

Length of rotor (4):

$$L = \frac{\pi\lambda D_{is}}{2p_1} \tag{4}$$

Pains of permanent magnet (5) [2]:

$$d_m = g.\frac{B_e/B_g}{1-B_e/B_g} \tag{5}$$

where, $\mathbf{\widehat{B_v}} = \frac{4}{\pi}\cdot\frac{p}{v}\cdot \mathbf{B_\delta}\cdot\mathbf{sin}\left(\frac{\alpha\pi}{2p}\right)\cdot\mathbf{sin}\left(\mathbf{v}\frac{\pi}{2p}\right)$; $\mathbf{\widehat{A_p}} = \boldsymbol{\xi_p}\cdot\sqrt{\mathbf{2}}\cdot\frac{w_{coil}\cdot I_{coil}}{\tau_s}$; and $\mathbf{v} = \boldsymbol{\pi}\left(\frac{D_a}{2}\right)^2$.

From this we have the rotor of a wind generator with a surface magnet shown in Figure 3. How to mount this type of magnet: on the rotor, cut 12 slots on the rotor steel and on the magnet, cut 2 slots to mount the magnet (will cut before loading the magnet). When installing, mount the magnet carefully to avoid breaking the magnet. In the simulation, the author ignores the slots to mount the magnet. In the simulation, use Ndfe30 magnets shown in Figure 4.

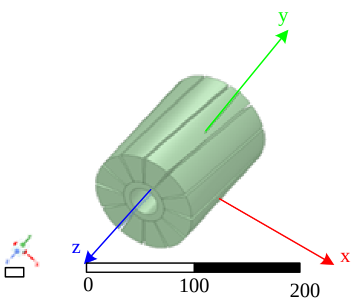

Figure 3. Rotor of wind turbine

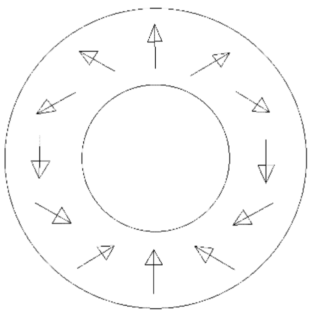

Figure 4. Rotor with Halbach permanent magnet

The winding set of electric phases A, B, and C is shown in Figure 5. Figure 5 shows the wiring diagram of a SG consisting of 18 slots and folded windings. With pairs of windings A-X, B-Y, and C-Z. This is a complete set of input and output windings for vertical axis wind turbine generator applications.

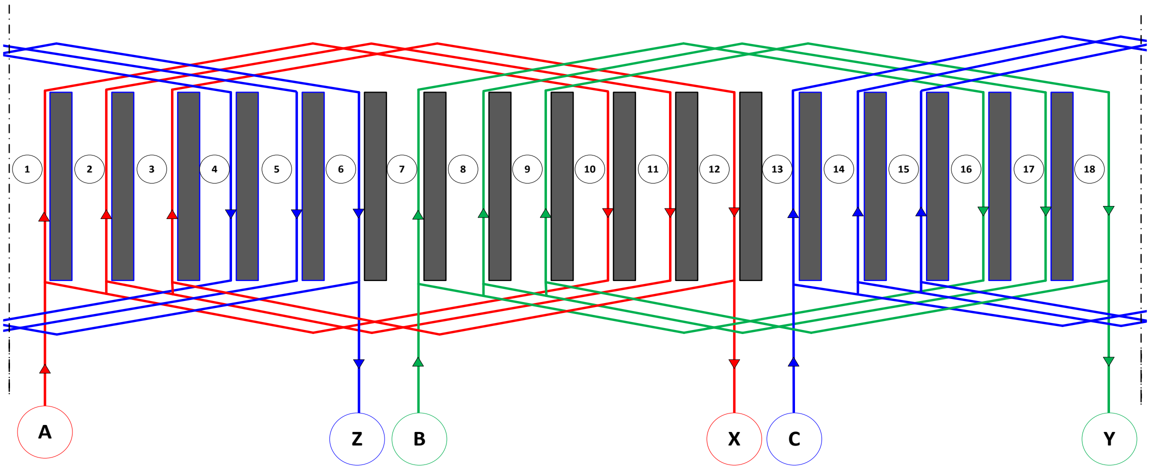

Figure 5. Winding of stator

3. RESEARCH AND DESIGN AN ADAPTIVE SLIDING MODE CONTROLLER USING SENSORLESS PMSM MOTORS FOR INDUSTRIAL ELECTRIC DRIVE SYSTEMS

From the above research content, we have the following input data as Table 1. Applying analytic manner to calculate and design generator, finite element manner indicate realizable for using alone turbine to design. ANSYS Maxwell is software to simulation machine by using finite element analysis (FEA).

Table 1. Main parameters

Symbol	Parameter	Normal	Halbach	Unit
n_N	Rotation speed norm	3000	3000	Rpm
Pgen	Power norm	1.274	74.906	kW
T_N	Moment norm	12.5	360	Nm
$E_{PM}=U_{rms}$	Voltage	64	500	V
L	Length of cores	230	230	mm
Nph	The number of winding on slot	84	84	-
N_s	The number of stator	18	18	-
B_r	Remanence of PM	1.3	1.3	T
D_i	Inner stator	175	175	mm
D_o	Outer stator	253	253	mm
h_{PM}	Thickness of PM	50	50	mm
W_{PM}	Width of PM	41.09	41.09	mm
p	The number of poles	1	1	-

The application of methods for generator calculation and design, the finite element method has reliability for wind turbine simulation. ANSYS Maxwell is a software for simulating electrical machines by FEA following Maxwell's equations [8], [9].
According to Faraday's law of induction:

$$\nabla \times E = \frac{\partial B}{\partial t} \tag{6}$$

Calculation expression according to Gauss's law of magnetic field:

$$\nabla \cdot B = 0 \tag{7}$$

Ampere's law:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (8)$$

Calculation expression, about Gauss's law of electric field:

$$\nabla \cdot D = \rho \quad (9)$$

3.1. Rotor has normal permanent magnet

From the above studies, we have the following simulation results. The rotor using permanent magnets operates due to the interaction between the fixed magnetic field of the magnet and the magnetic field of the stator, as shown in Figure 6 (magnetic field density). Figure 7 shows the value of current, Figure 8 shows voltage, and Figure 9 illustrates the torque-speed characteristics. The use of normal permanent magnet rotors in synchronous machines helps increase power density, improve efficiency and reduce energy consumption for the machine.

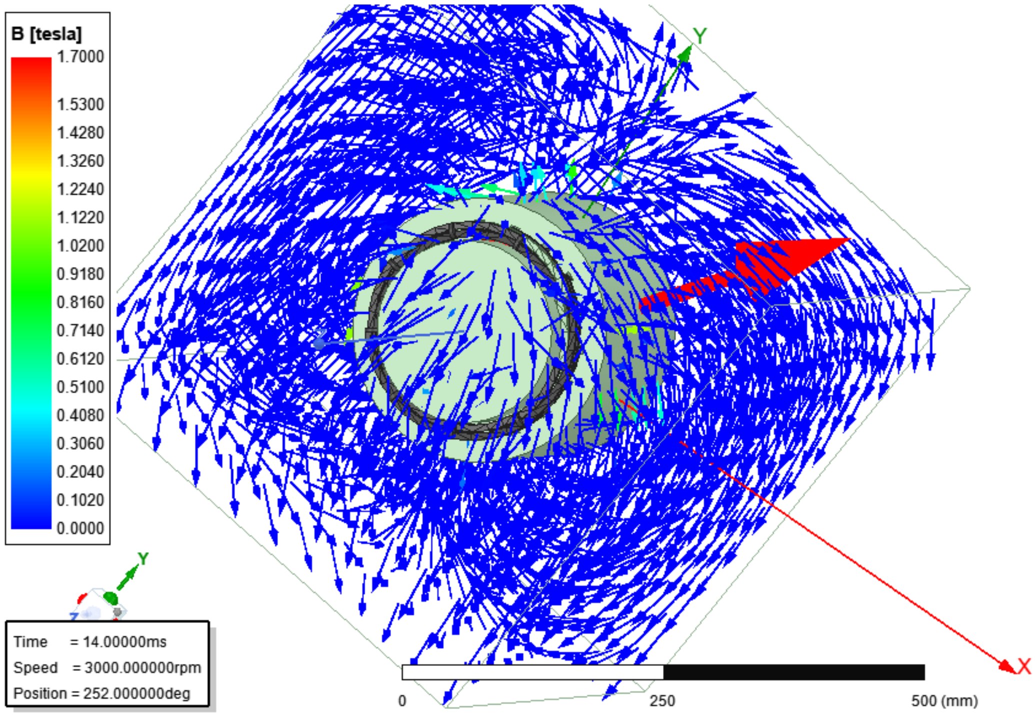

Figure 6. Flux density

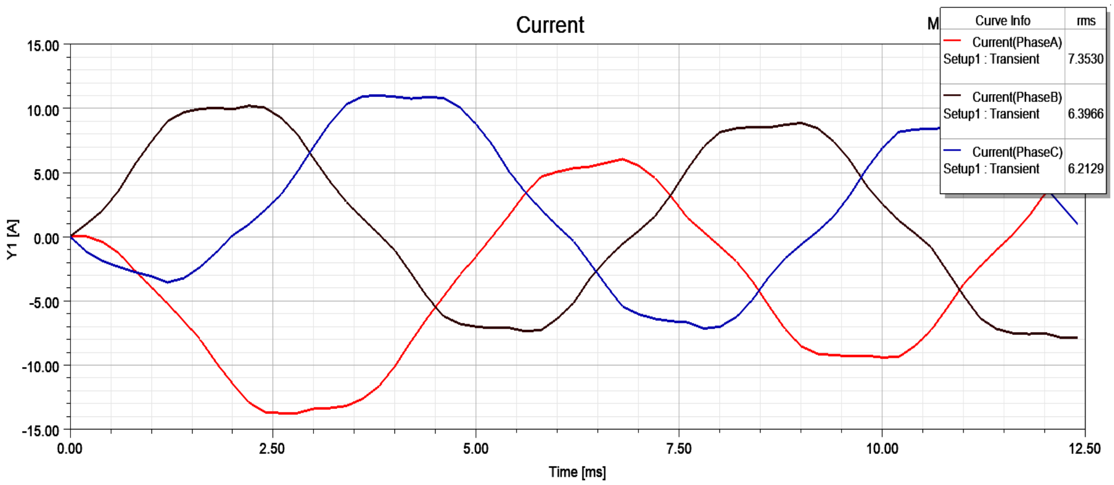

Figure 7. Current at normal PM

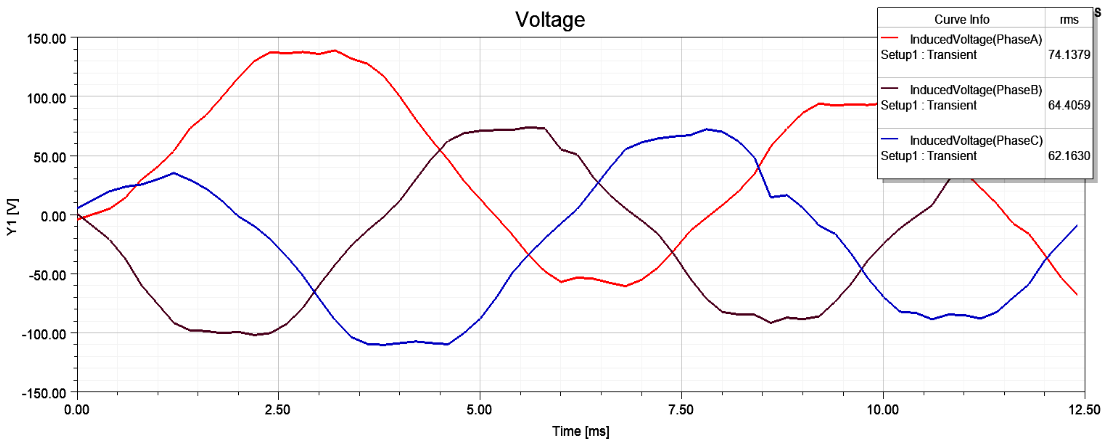

Figure 8. Voltage at normal PM

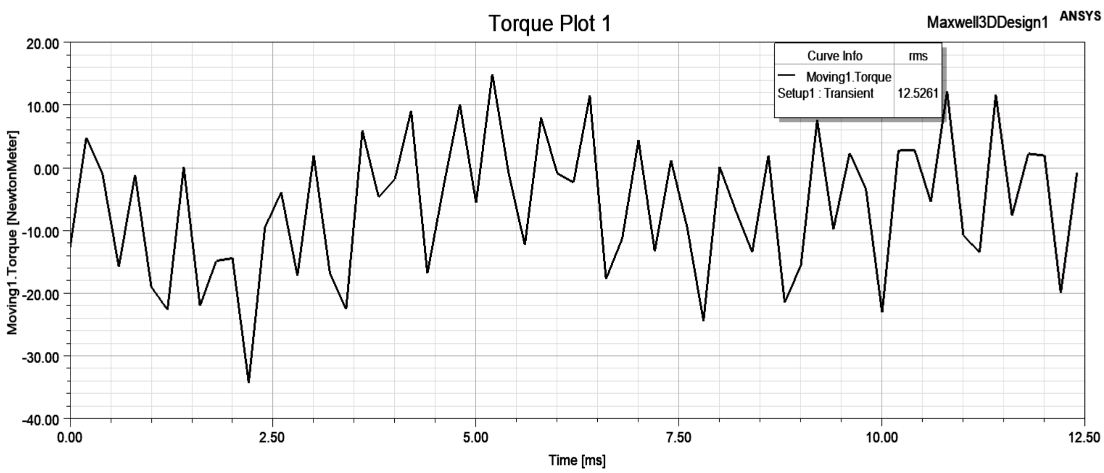

Figure 9. Momen-speed characteristic at normal PM

Depend on Figures 7 and 8, cosφ=1 generate power is (10) and (11):

$$S_{gen1} = S_a + S_b + S_c = 74 * 7 + 64 * 6 + 62 * 6 = 1274\ W \quad (10)$$

$$P_{gen} = S_{gen1}.\cos\varphi = 1274 * 1 = 1{,}274\ kW \quad (11)$$

Turbine power is (12):

$$P_{shaft} = \frac{T.n}{9.55} = \frac{12{,}5*3000}{9.55} \approx 3926\ W \quad (12)$$

From (11) and (12), efficiency of turbine is (13):

$$\eta = \frac{P_{gen1}}{P_{shaft}} = \frac{1274}{3926} = 32.4\% \quad (13)$$

3.2. Rotor has Halbach permanent magnet

From the above studies, we obtained have the following simulation results with a rotor equipped with Halbach magnets. The results show that the use of wind turbines with Halbach magnet configuration brings significant benefits. Wind turbines with surface magnets have the advantage of easy material search in Vietnam for design and manufacturing research. In addition, the simple machine structure facilitates mass production, the software testing process shows that the mechanical properties of the machine always have

better stiffness than some common types of motors (asynchronous motors and synchronous motors) currently on the market.
Depend on Figures 10 and 11, cosφ=1 generate power is (14) and (15):

$$S_{gen2} = S_a + S_b + S_c = 498 * 49 + 540 * 54 + 464 * 46 = 74906\ W \tag{14}$$

$$P_{gen2} = S_{gen} * cos\ \varphi = 74906 * 1 = 74{,}906\ kW \tag{15}$$

Turbine power is (16):

$$P_{shaft2} = \frac{T*n}{9.55} = \frac{360*3000}{9.55} \approx 113089\ W \tag{16}$$

From (15) and (16), efficiency of turbine is (17):

$$\%\eta_2 = \frac{P_{gen2}}{P_{shaft2}} = \frac{74906}{113089} = 66.2 \tag{17}$$

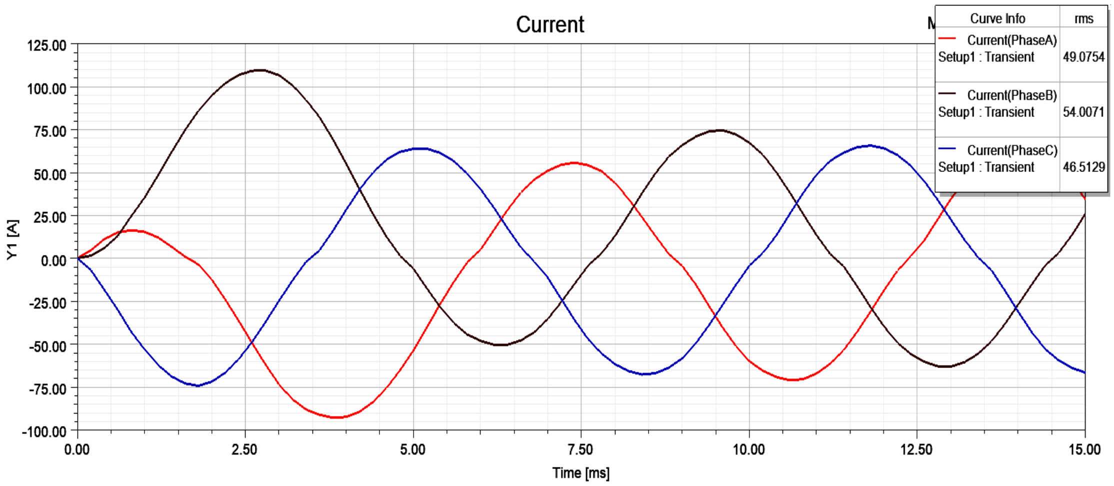

Figure 10. Current at Halbach PM

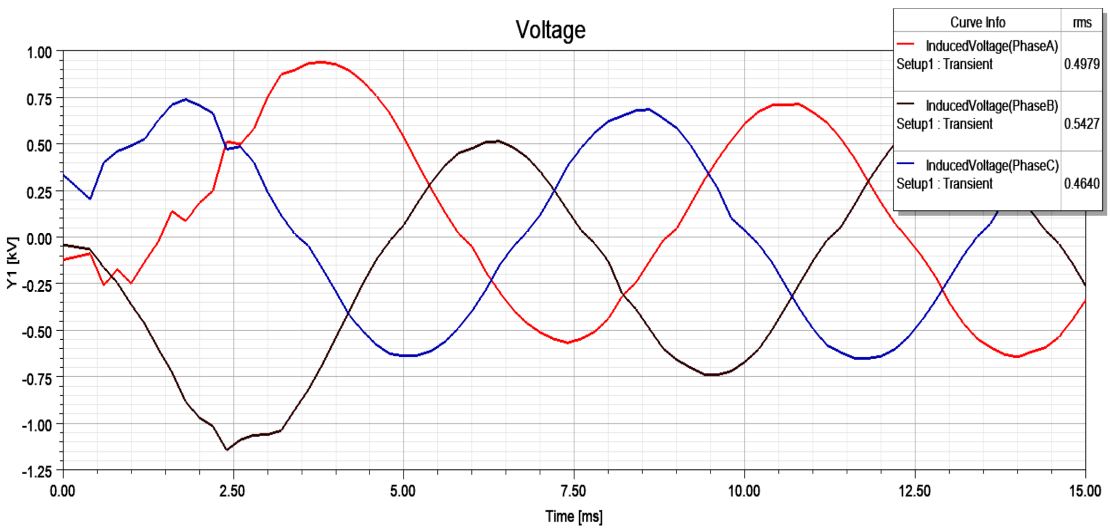

Figure 11. Voltage at Halbach PM

From Figures 9 and 12, it can be seen that the torque characteristic in Figure 12 is more stable. In contrast, Figure 9 shows that the machine has significant vibration and noise. With the same machine size, changing the magnet type increases the output power by about 70 times. This means that with the same power level, the machine size can be significantly reduced.

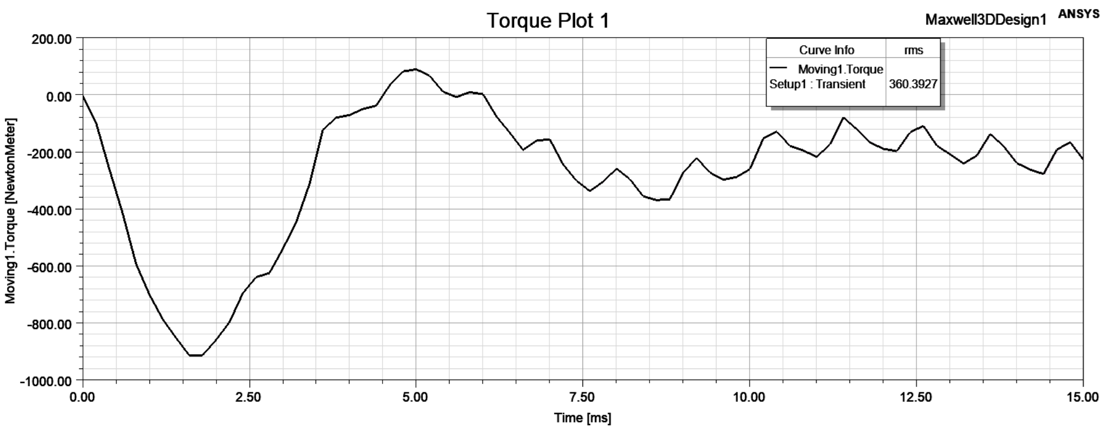

Figure 12. The momen-speed characteristic at Halbach PM

The generator design presented in this paper has the following differences from existing generators. Improved performance: the newly designed permanent magnet synchronous generator (SPM) has higher performance thanks to optimized magnetic flux and reduced energy loss, saving energy during operation. Reliability and maintenance: the simple structure of the SPM reduces maintenance requirements and increases reliability in long-term operation. Manufacturing costs: the use of rare earth magnets with optimized design reduces manufacturing costs, making the SPM generator a more economical and superior choice.

4. CONCLUSION

The wind turbine system the authors studied, including wind turbines designed with Halbach magnet configuration brings many benefits. The use of rare earth magnets helps reduce material costs, opening up great potential for the renewable energy industry in the future, both in Vietnam and in the world. For this generator, when applied to the field of application as a vertical axis wind turbine generator, or horizontal axis wind turbine, it is currently considered suitable to bring high efficiency and economy to the business. In addition, this Halbach PM generator is also widely used in the industrial field: hydroelectric generators, generators in electric cars, and electric vehicles. The research process of calculating the design with Halbach PM electric machine has many advantages in terms of higher torque and stability when compared with other conventional electric machines. The results of this research of the authors will bring new contributions to serve as a basis for a number of further research investigations in the coming time, including: new potential research areas from the design and manufacturing stages, calculations and to the control of electric machines based on optimization techniques such as genetic algorithms (artificial intelligence) and sustainable optimization (electrical equipment).

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Phan Hoai Nam	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Tran Duc Chuyen	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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