APPLICATION OF NUMERICAL METHODS TO INVESTIGATE THE INFLUENCE OF LONG-DUARATION VOLTAGE VARIATIONS OF THE DISTRIBUTION GRID ON THE PERFORMANCE CHARACTERISTICS OF LINE-START PERMANENT MAGNET SYNCHRONOUS MOTORS

ỨNG DỤNG PHƯƠNG PHÁP SỐ KHẢO SÁT ẢNH HƯỞNG CỦA HIỆN TƯỢNG DAO ĐỘNG ĐIỆN ÁP TRÊN LƯỚI ĐIỆN PHÂN PHỐI ĐẾN ĐẶC TÍNH LÀM VIỆC CỦA ĐỘNG CƠ ĐỒNG BỘ NAM CHÂM VĨNH CỬU KHỞI ĐỘNG TRỰC TIẾP

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DOI: http://doi.org/10.57001/huih5804.2025.002

ABSTRACT

Currently, permanent magnet synchronous motors with on-line starting are being increasingly researched and applied to partialy replace squirrel cage asynchronous motors, which are commonly used. The reason is that these motors have many advantages such as high efficiency, and high power factor value, stable speed, higher power density compared to induction motors, and the ability to self-start. However, like other motors, during operation, these motors are affected by external factors such as voltage, supply frequency, which impact operational parameters, especially power factor and efficiency. With the power supply, the voltage from the distribution grid usually fluctuates depending on the time of day, month, season, and is typically maintained within permissible limits. To assess the impact of long-duaration voltage variations of the distribution grid, the paper applies numerical methods to investigate the characteristics and parameters of the motor when this phenomenon occurs. Based on the research results, the paper will propose some solutions to prevent negative effects caused by long-duaration voltage variations to ensure the reliability of motor operation in the system.

Keywords: *Line-Start Permanent Magnet Synchronous Motors; Permanent Magnet; Synchronous Motors; numerical method; voltage variations.*

TÓM TẮT

Động cơ điện đồng bộ nam châm vĩnh cửu khởi động trực tiếp được nghiên cứu và ứng dụng ngày càng nhiều nhằm thay thế từng phần cho động cơ không đồng bộ rôto lồng sóc đang phổ biến hiện nay. Động cơ này có ưu điểm như hiệu suất cao, cosφ lớn, tốc độ ổn định, mật độ công suất lớn và khả năng tự khởi động. Tuy nhiên động cơ chịu tác động của yếu tố bên ngoài như điện áp, tần số nguồn cấp,… ảnh hưởng đến đặc tính làm việc, đặc biệt là hệ số công suất và hiệu suất. Điện áp của lưới điện phân phối thường dao động tuỳ thời điểm trong ngày, tháng, mùa và được duy trì ở giới hạn cho phép. Để xem xét ảnh hưởng của hiện tượng dao động điện áp trên lưới điện phân phối, bài báo ứng dụng phương pháp số để khảo sát các đặc tính và thông số của động cơ. Từ kết quả nghiên cứu, một số giải pháp sẽ được bài báo đưa ra để ngăn ngừa các ảnh hưởng tiêu cực do hiện tượng dao động điện áp nhằm đảm bảo độ tin cậy trong vận hành của động cơ trong hệ thống.

Từ khóa: *Động cơ đồng bộ nam châm vĩnh cửu khởi động trực tiếp; nam châm vĩnh cửu; động cơ đồng bộ; phương pháp số; dao động điện áp.*

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Received: 25/9/2024
Revised: 22/11/2024
Accepted: 24/01/2025

1. INTRODUCTION

The Line Start Permanent Magnet Synchronous Motor (LSPMSM) has been proven to have advantages in steady state operation, such as having high electromechanical conversion efficiency, a power factor close to 1, and high power density [1, 2]. In recent decades, many researchers have studied and applied LSPMSM as a partial replacement for the widely used induction motors. The LSPMSM is essentially an improvement of both the permanent magnet synchronous motor and the induction motor. In other words, it is a hybrid motor between the squirrel cage induction motor (SCIM) and the permanent magnet synchronous motor, combining the advantages of both types in operation [3, 4].

However, in practice, there are many factors influencing the working parameters of the LSPMSM during operation. One of these factors is the power supply. Among the power supply-related incidents, the phenomena of long duaration voltage variation (PLDVV) on the distribution grid are the most common [5, 6]. Many studies have shown that PLDVV result in losses in the rotor and stator windings directly reducing the operational efficiency of the motor. Additionally, PLDVV can affect the torque, speed, efficiency, and power factor (cosφ) of the motor [6]. In reality, in distribution grid of low-voltage operation, factors such as electrical load demand, weather conditions, electricity generation output of power plants, etc., cause the voltage value of the power supply to be unstable and constantly changing over time. The frequency of PLDVV tends to increase during peak electricity usage times, or increase midweek and decrease during the weekends [7-9].

To investigate the impact of PLDVV on the characteristics and working parameters of LSPMSM, the paper utilizes software applying the Finite Element Method (FEM) to model and simulate some working characteristics as well as the relevant working parameters of the motor. Specifically, in Sec. 2, the paper briefly summarizes the basic theory of LSPMSM motors, numerical methods, and the software employing numerical methods in simulating electric machines. Sec. 3 examines the influence of PLDVV on LSPMSM under various scenarios. Based on the results obtained, the paper will analyze, evaluate, and draw conclusions to maintain stable motor operation in the face of PLDVV on the distribution grid. In the study, the paper conducts experiments on a 3-phase, 4-pole, 380/220VAC, 2.2kW LSPMSM.

2. LINE START PERMANENT MAGNET SYNCHRONOUS MOTOR AND SIMULATION METHOD

2.1. LSMPSM rotor configuration

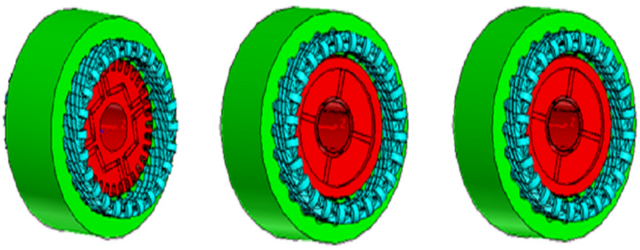

Figure 1. Rotor designs of LSPMSM with inserted permanent pagnet rods [Source:10]

The LSPMSM stator is fundamentally similar to an asynchronous motor. However, the LSPMSM has a structure similar to an asynchronous motor, but within the rotor core, there are inserted permanent magnet bars. Some common rotor configurations of LSPMSM nowadays are shown in Fig. 1.

2.2. Modeling of LSPMSM

In simulating LSPMSM, researchers commonly employ two methods: analytical simulation through mathematical models and numerical simulation. For analytical simulation, in LSPMSM researchs, authors such as Takahashi, Aliabad, Kwang Hee Kim... [11-13] utilize the mathematical model of LSPMSM proposed by Honsinger to investigate the motor's performance characteristics. In summary, the mathematical model of LSPMSM is expressed in the form of differential equations as follows:

Voltage equations:

Stator voltages

$$\begin{cases} v_{ds} = r_s.i_{ds} + \dfrac{d\psi_{ds}}{dt} - \omega_m.\psi_{qs} \\ v_{qs} = r_s.i_{qs} + \dfrac{d\psi_{qs}}{dt} + \omega_m.\psi_{ds} \end{cases} \quad (1)$$

Rotor voltages

$$\begin{cases} v'_{dr} = r'_{dr}.i'_{dr} + \dfrac{d\psi'_{dr}}{dt} = 0 \\ v'_{qr} = r'_{qr}.i'_{qr} + \dfrac{d\psi'_{qr}}{dt} = 0 \end{cases} \quad (2)$$

Flux equations:

Stator fluxes

$$\begin{cases} \psi_{ds} = (L_{ls} + L_{md}).i_{ds} + L_{md}.i'_{dr} + \psi'_m \\ \psi_{qs} = (L_{ls} + L_{mq}).i_{qs} + L_{mq}.i'_{qr} \end{cases} \quad (3)$$

Rotor fluxes

$$\begin{cases}\psi'_{dr} = L'_{lr}.i'_{dr} + L_{md}.(i_{ds} + i'_{dr}) + \psi'_m \\ \psi'_{qr} = L'_{lr}.i'_{qr} + L_{mq}.(i_{qs} + i'_{qr})\end{cases} \quad (4)$$

Torque equations:

$$T_{el} = \frac{3}{2}.p.\left[\begin{array}{l}\underbrace{\left(L_{md}.i'_{dr}.i_{qs} - L_{mq}.i'_{qr}.i_{ds}\right)}_{\text{induction torque element}} \\ + \underbrace{\Psi'_m.i_{qs}}_{\text{excitation torque element}} + \underbrace{(L_{md} - L_{mq}).i_{ds}.i_{qs}}_{\text{reluctance torque element}}\end{array}\right] \quad (5)$$

Where r_s is the stator resistance, L_{ls} is the stator leakage inductance, L_{md}, L_{mq} are the d-q axis synchronous magnetizing inductances, respectively and ω_m is the electrical angular frequency of the rotor. v_{ds} and v_{qs} are the d-q axis stator voltages, v'_{dr} and v'_{qr} are the d-q axis rotor induced voltages, ψ_{ds} and ψ_{qs} are the d-q axis stator flux linkages, ψ'_{dr} and ψ'_{qr} are the d-q axis rotor flux linkages, r_s is the stator resistance, r'_r is the total equivalent rotor resistance and T_{el} is the electromagnetic torque of the motor.

2.3. Numerical methods for simulating eletromagnetic fields

Besides simulating the motor's operation through the analytical modeling method as mentioned in section 2, nowadays, thanks to the advancement of computer technology, numerical methods are commonly applied for electric machine simulations. Currently, there are various numerical methods used in solving problems related to the eletromagnetic fields of electric machines. The most common numerical methods today include the Finite Difference Method (FDM), the Boundary Element Method (BEM), the Finite Element Method (FEM), and the Discrete Element Method [14]. These methods all enable the approximate solution of partial differential equations in electromagnetic field problems.

Among the numerical methods currently used, FEM has been recognized for its high accuracy in approximating integral equations in problems related to electromagnetic devices. Therefore, in this study, the paper employs FEM simulation software to investigate the characteristics of LSPMSM and evaluate the impact of PLDVV on LSPMSM. Additionally, among the software utilizing FEM for electromagnetic device simulations such as FEMM, Opera (Cobham), MagNet V7 (Infolytica), Ansys/Maxwell, Ansys/Maxwell is widely applied by researchers and electrical machine designers today.

3. SIMULATING THE IMPACT OF THE PHENOMENA OF LONG DUARATION VOLTAGE VARIATION ON THE LINE START PERMANENT MAGNET SYNCHRONOUS MOTOR

3.1. The phenomena of long duaration voltage variation of distribution grid

The PLDVV on the distribution grid over time is defined as variations in the effective values at the supply frequency over a duration exceeding 60 seconds [15]. According to the ANSI C84.1 standard, the permissible tolerance level of voltage in the steady state on the distribution system is also defined. A variation in voltage is identified as a PLDVV over time when its effective value exceeds the limit specified by ANSI for a duration greater than 60 seconds.

PLDVV over time includes two levels: Overvoltage and undervoltage. Overvoltage and undervoltage are generally not system faults but are primarily caused by load variations and switching operations on the system. The PLDVV over time in the power system typically varies by the time of day, week, or season and is a result of changes in load demand on the system. Additionally, the use of large power equipment such as welding stations, high-power motor, and furnaces can also lead to voltage drops in the system [16]. This PLDVV is usually represented in the form of effective voltage values over time. Fig. 2 illustrates PLDVV on a low-voltage distribution system over time during the day.

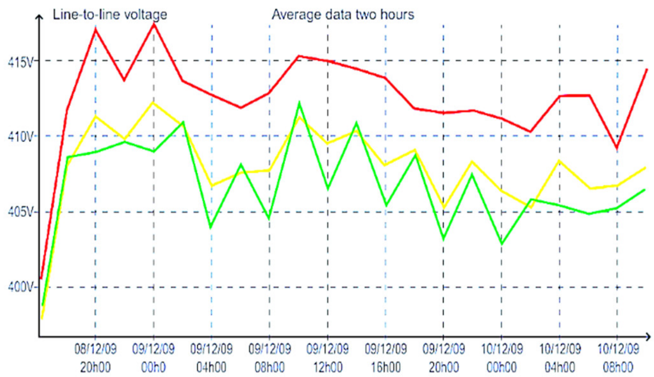

Figure 2. The voltage values throughout the day (source [16])

3.2. Experimental configuration of LSPMSM

To investigate the impact of PLDVV on the working characteristics of LSPMSM on the istribution grid, the paper utilizes a 3-phase experimental LPSMSM, rated at 2.2kW, 380/220V, 2p = 4. The configuration of the experimental LSPMSM is shown in Fig. 3.

The parameters of the experimental LSPMSM are described in Table 1.

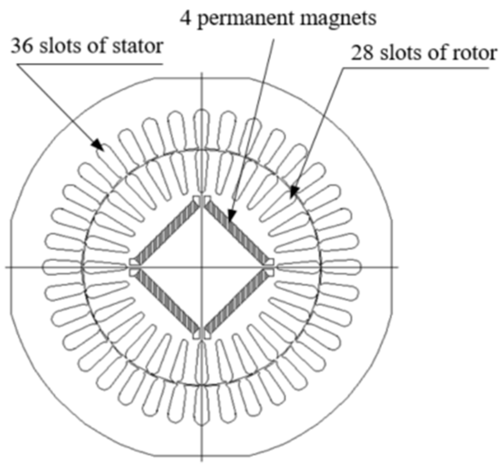

Figure 3. Experimental configuration of LSPMSM 2.2kW, 2p = 4

Table 1. The parameters of the experimental LSPMSM 2.2kW

Parameters	Symbols	Values	Units
The outer diameter of the stator	D_n	170	mm
The inner diameter of the stator	D	104	mm
The outer diameter of the rotor	D'	103	mm
The shaft diameter of the rotor	D_t	35	mm
Steel material	Steel 1008		
The number slots of stator	Z_1	36	Slot
The number slots of rotor	Z_2	28	Slot
Air gap	g	0.5	mm
Power supply voltage	U_n	380/220	V
Power supply frequency	f	50	Hz
Permanent magnet material	NdFeN35		
Width of permanent magnet rod	w_m	34	mm
Thickness of permanent magnet rod	l_m	5	mm
Rated load torque	T_L	14	Nm

3.3. Simulating the impact of phenomena of long duaration voltage variation on the working parameters of the LSPMSM

To investigate the impact of the PLDVV on the performance of LSPMSM as mentioned in Section 1, the paper conducts simulations on the PLDVV and the characteristics of LSPMSM under these conditions. The results considered are speed and current characteristics, as these two parameters are crucial in demonstrating the starting and working ability of the motor. Additionally, the paper also determines the power factor and efficiency of the motor through simulations, as these parameters significantly affect the motor's operational efficiency.

Additionally, according to the general regulations, the permissible level of voltage of the PLDVV on the low-voltage distribution grid in Vietnam and some countries is ±10% of the rated voltage of the distribution system [17]. Also, as per these regulations, the rated voltage of the low-voltage distribution system in Vietnam and some countries is 220/380V. Therefore, the paper will simulate the experimental LSPMSM under various scenarios where the voltage fluctuates within the corresponding voltage range: 200V, 210V, 220V, 230V, and 240V. The voltage levels in these simulation scenarios fall within the voltage range specified for the PLDVV, ranging from -10% to +10% of the rated voltage of the low-voltage distribution system.

3.3.1. Speed characteristic simulation

The paper simulates the speed characteristic of the 2.2kW experimental LSPMSM with the parameters provided in Table 1 and the voltage levels according to the scenario mentioned in 3.3. The speed characteristic simulation is illustrated in Fig. 4.

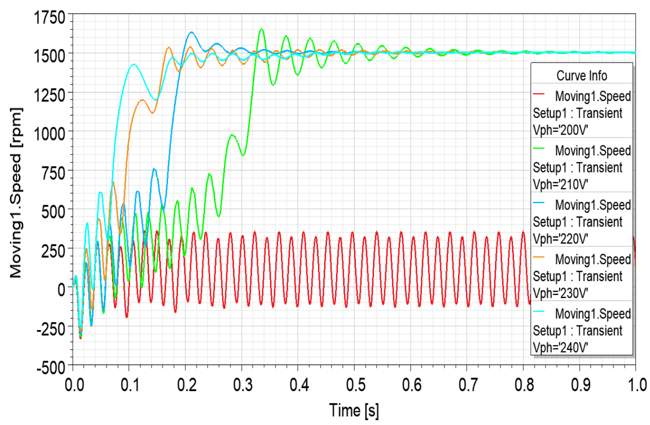

Figure 4. Speed characteristic simulation with the LSPMSM 2.2kW

From Fig. 4 at the same rated load level, it can be observed that as the grid voltage value increases, the motor starting becomes easier. With higher voltage, the motor reaches its maximum speed in a shorter time and enters stable synchronous speed operation sooner. In the worst-case scenario of a 10% voltage drop (200V), the motor fails to start at rated load. A higher supply voltage makes it easier to start the motor. This can be explained as follows: according to [18, 19], during the starting process, the average squirrel cage torque is positive and contributes to rotor acceleration. In contrast, the average value of the total excitation torque and the reluctant torque is negative (breaking torque) acts as a break of the motor. Furthermore, the squirrel cage torque is proportional to the square of the supply voltage; therefore, the higher the supply voltage, the easier it is for the motor to start.

3.3.2. Current characteristic simulation

The current characteristic of one phase (phase A) when simulated with different voltage level scenarios in the presence of the PLDVV on the distribution grid as shown in Fig. 5.

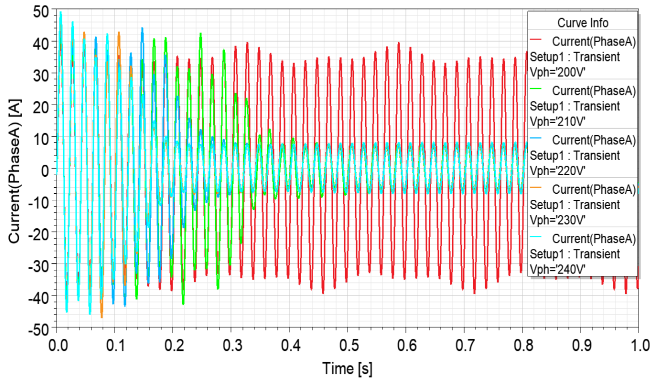

Figure 5. Current characteristic simulation with the LSPMSM 2.2kW

From Fig. 5, it can be observed that during motor startup time, the current rises significantly, with the highest peak current magnitude corresponding to the highest input voltage level (240V). The starting current value at this point can be up to 4 times the operating current in steady state mode. Additionally, it is also noted that as the voltage supplied to the motor increases, the time for the current to transition into stable operating mode decreases. At 200V, as indicated in the speed characteristic in Fig. 4 showing the motor's failure to start, same as in Fig. 5, the current characteristic remains akin to the startup mode (high phase current) for an extended period.

3.3.3. Efficiency and power factor simulation

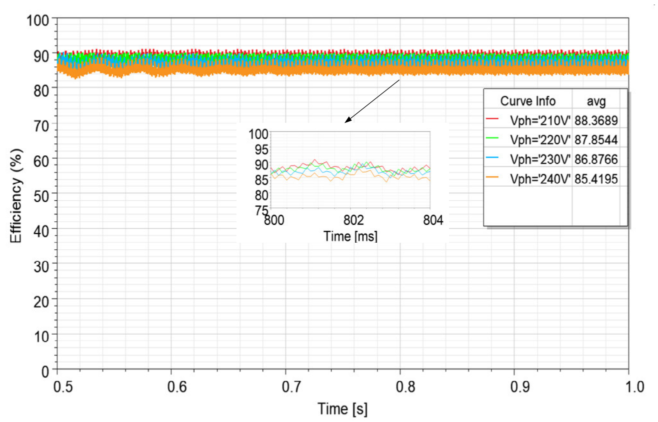

Figure 6. Efficiency characteristic simulation with the LSPMSM 2.2kW

The efficiency and power factor characteristic when the motor operates in a stable mode as shown in Figs. 6 and 7. Since the motor fails to start at 200V, this voltage level is not considered in the paper when simulating the motor's operating efficiency and power factor in Figs. 6 and 7.

From Fig. 6, the paper calculates the average working efficiency value of the motor during the time interval of 0.5 to 1 second, which represents the period when the motor operates steadily. The average calculated value during that time interval is illustrated in Fig. 6 Through simulation, it can be observed that as the input voltage decreases, the motor efficiency increases. The maximum efficiency of the motor is 88.4%, corresponding to an input voltage of 210V.

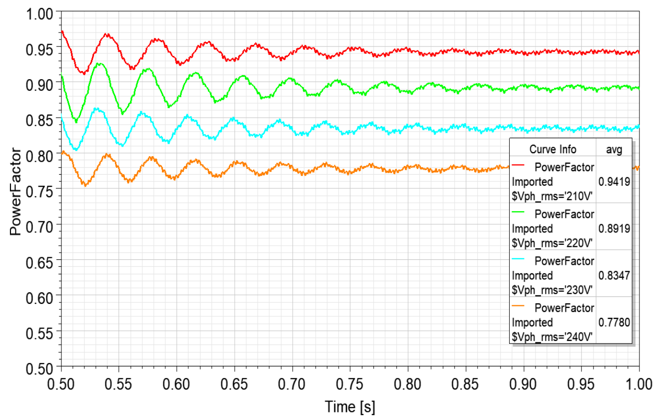

Figure 7. Power factor characteristic simulation with the LSPMSM 2.2kW

From Fig. 7, the paper calculates the average working power factor value of the motor during the time interval of 0.5 to 1 second, which represents the period when the motor operates steadily. The average calculated value during that time interval is illustrated in Fig. 7. Through simulation, it can be observed that as the input voltage decreases, the power factor of the motor increases. The maximum power factor of the motor is 0.94, corresponding to an input voltage of 210V. When the voltage is low, the efficiency and power factor of the motor increase, which can be explained as follows: In a steady state, a LSPMSM functions like a synchronous motor. Additionally, the LSPMSM is excited by the permanent magnets, so the no-load electromotive force E_0 of the motor remains constant during this operation. For synchronous motors, when the supply voltage U_n is higher than E_0, the motor typically operates in a state of under-excitation, consuming reactive power from the power supply. This leads to an increase in the motor's power factor, which consequently results in a decrease in the motor's efficiency.

4. CONCLUSION

The research paper investigates the impact of the PLDVV over time on the characteristics and two main operating parameters of LSPMSM motors, namely efficiency and power factor. In the study, the paper utilizes FEM software to simulate the characteristics and parameters of the motor and applies it to simulate the experimental 2.2kW, 2p = 4 LSPMSM. To assess the influence of the PLDVV, the paper presents several simulation scenarios with varying effective voltage levels supplied to the motor. The voltage levels in these scenarios fall within the permissible voltage range as stipulated by regulations concerning the PLDVV in power systems.

The simulation results demonstrate that the PLDVV over time have a significant impact on the operating parameters of LSPMSM motors. Specifically, concerning speed characteristics, higher voltages improve the motor's starting capability and lead to faster stabilization. In the worst-case scenario with a low voltage of 200V, the motor fails to start. Regarding current characteristics, higher voltages result in the motor starting with a higher current. Furthermore, at 200V, where the motor cannot start, the current remains at a starting level throughout the power supply process. Prolonged starting times at this voltage level can lead to motor burnout. In such cases, users must intervene promptly by preventing motor start-up at low voltages or increasing the voltage before starting the motor. However, in terms of performance parameters, lower voltages correspond to higher motor efficiencies. Notably, at 210V and 240V, the corresponding efficiencies are 88.4% and 85.4%, showing a performance difference of nearly 3%. Similar to efficiency, in terms of power factor values, the lower the voltage, the higher the power factor. The maximum power factor is 0.94, corresponding to a voltage of 210V.

Thus, the PLDVV over time have a significant impact on the characteristics and operating parameters of LSPMSM motors. Users need to control the supplied voltage to ensure a balance between the starting voltage and operational voltage to avoid the worst-case scenario where the motor cannot start due to low grid voltage. Additionally, excessively high voltages should be avoided during operation as they can lead to lower motor efficiency and power factor values.

ACKNOWLEDGMENT

This paper is supported by research funding by HaUI's Project number 11-2024-RD/HD-DHCN, the authors would like to thank..

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