Simplified Current Sensorless Maximum Power Extraction for Wind Energy Conversion Systems

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ABSTRACT The penetration of wind energy conversion systems (WECSs) have been substantially expanded over the last few years. Maximum Power Extraction (MPE) is one of the most efficient and reliable techniques for controlling the power converter of the generator. This research aims to present a simplified MPE that retains the benefits of the conventional MPE while significantly reducing the control loop complexity. By taking into account the wind velocity and disturbances, the proposed approach reformulates machine equations and controls the voltages and currents on $dq$-plane to drive the wind turbine at optimum performance. Furthermore, it does not require current and voltage measurements and waives the need for intricate tuning operations. The proposed simplified MPE controller’s speed and power tracking performances are assessed through many simulations and experimental tests in various scenarios, and the results are compared to the vendor’s datasheets as well as the field-oriented control method to prove its excellence.

INDEX TERMS Maximum power extraction, voltage source converter, variable speed wind turbine.

NOMENCLATURE

A. LIST OF ACRONYMS
IPMSG Interior Permanent Magnet Sync. Gen.
MEPT Maximum Electrical Power Tracking.
MMPT Maximum Mechanical Power Tracking.
MPE Maximum Power Extraction.
MPP Maximum Power Point.
MPPT Maximum Power Point Tracking.
MPA Maximum Torque Per Ampere.
PMSG Permanent Magnet Synchronous Generator.
SPMSG Surface-mount Permanent Magnet Sync. Gen.
VSWT Variable Speed Wind Turbine.
WECS Wind Energy Conversion Systems.

B. LIST OF SYMBOLS

- $P_w$, $P_{opt}$: Turbine mechanical and optimum power.
- $P_e$: Electrical generated power.
- $T_m$, $T_e$: Mechanical and electrical torque.
- $\rho$: Air density.
- $v_w$: Wind velocity.
- $A_R$: Blade swept area.
- $R_r$: Radius of the turbine blades.
- $C_p$: Rotor power coefficient.
- $\lambda_w$, $\vartheta$: Tip speed ratio and pitch angle.
- $\omega_{opt}$, $\omega$: Optimum and mechanical rotor speed.
- $\tau_{opt}$: Optimum mechanical torque.
- $v$, $\theta_v$: Stator voltage amplitude and angle.
- $v_d$, $v_q$: Stator voltage in $dq$-plane.
- $i_d$, $i_q$: Stator current in $dq$-plane.
- $L_d$, $L_q$: Inductance in $dq$-plane.
- $R$: Armature resistance.
- $\lambda$: Permanent magnet flux linkage.
- $\theta$: Rotor electrical position.
- $J$: Rotor and load inertia.
- $p$: Number of pole pairs.
- $v_{a\beta}$: Voltages in $a\beta$-plane.
- $\tau_F$, $\tau_L$, $\tau$: Friction, load, and motor torque.

I. INTRODUCTION

Climate change and global warming have become major concerns around the world, and many groups and governments are working to implement green energy regulations [1]. Wind surpassed all other renewable energy sources in 2020. Per
the US Energy Information Administration, the overall share was 300 million MWh, up 10 percent from the prior year [2]. Wind power is expected to expand its market share to 917 GW by 2030, according to forecasts from the Global Wind Energy Council. Because of its low environmental impact, comparatively low cost, and significant energy generation potential [3].

Fixed-speed wind turbine and variable-speed wind turbine (VSWT) are two primary types of wind energy conversion systems (WECSs). A back-to-back power converter splits a VSWT from the electricity grid [4]. Other features of VSWT include increased power capture and the capacity to function at peak efficiency, reduced mechanical stress and electrical ripples, and a greater degree of maneuverability [5], [6].

As a wind turbine generator, a myriad of electric machines can be used. The switch reluctance generator (SRG) has a simple design and ease of maintenance, but it requires an excitation mechanism and a precise position sensor [6].

A self-excited induction generators (SEIGs) have good dynamics and are brushless, however the necessity for a gearbox, regular technical maintenance, inferior voltage control ability, and a costly excitation capacitor bank are some of the most essential considerations to address [7], [8], [9].

DFIGs (Doubly-fed induction generators) are also prevalent. Also, their active and reactive powers can be controlled separately to some levels. DFIGs, on the other hand, have a weak fault-crossing capability and require more components (such as gears and slip rings) [4], [6], [10], [11], [12], [13], [14].

A permanent magnet synchronous generator (PMSG) is one of the most commonly recommended types of machinery for wind turbine generators. A converter entirely isolates this generator from the electrical grid, and it has greater fault-crossing capabilities. It does not require an excitation system, does not produce magnetization current, has a higher power factor, reduced power losses, and surpasses its competitors in efficiency. A PMSG’s light weight and broad range of operational speeds are desirable attributes for a wind turbine generator whose rotational speed is affected by wind velocity changes. It also has a lower cut-in velocity than some other machines, making it ideal of this application [4], [5], [6], [15], [16].

In terms of the rotational speed of their tips, every wind turbine has four operational areas. The first zone is defined as the period between start and cut-in speed, once the turbine begins to generate energy. From the cut-in speed to the rated speed, the second area is where speed regulation and maximum power point tracking (MPPT) take place. When the wind velocity is strong enough for generation, power management is necessary in the third area, between the rated and cut-out values. In the fourth region, if the wind turbine exceeds the cut-out speed, it must be shut down to avoid any potential damage resulting from severe storms [17], [18].

Fathabadi investigated several maximum electrical power tracking (MEPT) and maximum mechanical power tracking (MMPT) systems. The conclusion is that MEPT methodologies outperform the latter in most cases [19]. Soliman et al. analyzed the performance of a wind turbine power converter using a linear-quadratic regulator (LQR) and grey wolf optimizer algorithms [5]. Haq et al. developed an MPE for tracking turbine speed based on the generalized global sliding mode control (GGSMC) [20]. Using a neural network model, they estimated the nonlinear drift factors and undertake a stability analysis through simulations. Sarsem-bayev et al. proposed an integral sliding mode control (ISMC) model based on a WECS-developed nonlinear feedback control [21].

In [22], a maximum power point tracking (MPPT) controller that regulates the entire system output power with the d-axis current of an active rectifier was designed and proven experimentally. This broad control approach has been the subject of several experiments [7], [23], [24], [25], [26]. In recent literature, researchers have combined maximum torque per ampere (MTPA) and maximum power extraction (MPE) for WECS to maximize efficiency while minimizing copper loss and avoiding excess heat. They determine the required torque for extracting the highest power from the given wind velocity, and the MTPA technique is used to calculate the minimal stator current necessary for acquiring the desired torque [27]. In [28], the reference speed is calculated using a neural network at any ambient temperature, wind velocity, and reference power. However, this technique is based on actual measured power, and the neural network needs to be trained for different sizes of wind turbines. Besides, a numerical method is employed to determine the exact pair of \( (v_d, v_q) \) for SPMSMs at various load torques and speeds [29].

This study contributes by presenting a straightforward MPE approach for a WECS. The proposed framework, unlike previous methods, does not involve any current or voltage measuring equipment and can be used immediately for any WECS; it also eliminates the need for frustrating tuning or training operations as well as numerical methods. The MPE guarantees that a wind turbine extracts maximum power, and thus the PMSG delivers the maximum electrical output. Combining the MTPA and MPPT methodologies ultimately maintains the highest operational performance of the WECS. The MPPT approach determines the optimal torque required by the PMSG to extract the maximum power at a given wind velocity. The minimum stator current is calculated using the MTPA. The PMSG must be regulated to provide the most power at the optimum torque and speed as determined by the MPPT trajectory. The power electronic bridge is operated according to the suggested technique for regulating the rotor speed and adapting the PMSG current towards the MTPA methodology’s minimal value indirectly. It calculates the desired optimal torque for attaining optimum output at varying wind velocities. Several simulations and experimental assessments of surface-mounted PMSGs (SPMSGs) support the efficacy of the proposed framework. In summary, the paper’s novelty comprises the following:
For a direct drive variable speed SPMSG based WECS, researchers propose a simple current sensorless control approach. The proposed technique is practical and can be simply adopted for industrial applications.

This study facilitates using MTPA and MPPT techniques to get the most available wind power out of the generator, even when the wind velocity varies. It also cuts down on stator current and copper losses.

Comprehensive simulations and experimental assessments of 300W and 2.4MW SPMSGs using a LabVIEW platform integrated with a National Instruments card PCI-6225 are used to justify the efficacy of the proposed framework.

The proposed technique is evaluated and compared to laboratory wind turbine manufacturer data as well as the well-known field-oriented control (FOC), demonstrating the effectiveness of the presented technology in terms of optimum speed tracking and power loss reduction.

Section II presents a broad review of the WECS, its mathematical foundations, and overall framework of the MPE approach. It also includes a detailed description of the recommended MPE design for the SPMSG. Section III exhibits the simulation and experimental findings, which are compared to the manufacturer’s data. Section IV provides a concise overview and a comprehensive conclusion to the research.

II. SIMPLIFIED MPE CONTROL STRATEGY FOR SPMSG

A. WIND ENERGY CONVERSION SYSTEM MODEL

The schematic diagram of the WECS that is investigated in this work is shown in Fig. 1. A wind turbine, an SPMSG, a 3-phase converter, and an MPE controller are all included. When the wind blows through, the blades’ aerodynamics create two low-pressure and high-pressure zones surrounding them, consequently rotating them. The SPMSG is rotated by the turbine, which transfers wind energy to electricity. The mechanical power \( P_w \) transmitted from the turbine to the generator is represented as (1), [30]:

\[
P_w = \frac{\rho}{2} C_p(\lambda_w, \vartheta) A_R \omega_w^3
\]  

The rotational speed of the turbine should match the maximum power points for every wind velocity in order for it to extract the maximum mechanical power \( P_{opt} \). This optimum rotor speed (\( \omega_{opt} \)) can be described as:

\[
\omega_{opt} = \frac{\omega_w}{R_c}
\]  

Substituting (2) and \( A_R \) in (1) yields the optimum mechanical power \( P_{opt} \):

\[
P_{opt} = \frac{\pi}{2} \rho \lambda_w^2 C_p \omega_{opt}^3
\]

Therefore, the optimum mechanical torque \( \tau_{opt} \)

\[
\tau_{opt} = \frac{\pi}{2} \rho \lambda_w^2 C_p \omega_{opt}^2
\]

The SPMSG is attached to a power electronics bridge, converting the AC voltage to a controlled DC voltage and feeding a load resistor. The current MPE proposal is executed as a drive for the generator to draw the maximum output power at given wind velocities. When the optimal rotor speed is maintained, maximum power is achieved. Thus, this study proposes a new SPMSG mathematical formula.

B. SIMPLIFIED MPE CONTROL TECHNIQUE

The machine equivalent circuit and mathematical model of the PMSG subedited in the \( dq \) rotating plane is shown in Fig. 2 and expressed by [31] as follows:

\[
v_d = Ri_d + L_d \frac{di_d}{dt} - L_q \omega_i q
\]
computes the optimum torque and rotor speed with regard to the wind velocity \( v_w \) fluctuations. Thus, the controller drives the PMSG at the reference rotor speed of \( \omega_{ref} \) to meet the criteria for maximum power extraction.

From (5c), varying configurations of \( i_d \) and \( i_q \) produce a specific torque. There is an optimal MPE solution among many \( i_d \) and \( i_q \) variables that may impose the very same torque as (4). According to the MTPA concept [32], [33], for surface-mounted PMSGs, \( i_d \) is equal to zero under nominal rotor speed and to consider reducing the magnitude of the stator current. By aligning the current vector with the q-axis, the rotor saliency absence allows MPE to be practical. With \( i_d = 0 \), the maximum power per amper can be derived as follows:

\[
v = \sqrt{(L_q p \omega i_q)^2 + (\omega \lambda + R i_q)^2}
\]

(10)

\[
\Delta \theta = \tan^{-1} \left( \frac{-L_q p \omega i_q}{\omega \lambda + R i_q} \right)
\]

(11)

Also, when \( L_q = L_d \) is replaced in (5c), the value of torque is directly proportionate to \( i_q \):

\[
\tau = \frac{3}{2} p \lambda i_q
\]

(12)

Finally, the q-axis current is as follows:

\[
i_q = \frac{2}{3p\lambda} \tau
\]

(13)

Under MPE conditions, the generator model can be derived from (8) and (9) as follows:

\[
v = p \omega \sqrt{\frac{2L_d}{3p\lambda}} \sqrt{\tau^2 + \lambda^2}
\]

(14)

\[
\Delta \theta = \tan^{-1} \left( \frac{p \omega L_d (2/3p\lambda) \tau}{(2R/3p\lambda) \tau + \lambda^2} \right)
\]

(15)

where (14) and (15) are equations representing the relationship between the voltage (amplitude \( v \) and angle \( \Delta \theta \)) and torque.

Equation (14) delineates the relationship between the voltage amplitude \( v \) and rotor speed \( \omega \). It is determined that the voltage \( v \) is directly proportional to the rotating speed of the SPMSG for a particular electromagnetic torque. However, the deviation slope is unreliable when a torque is applied. As a result, the voltage-speed change is characterized in such a way that maintains a direct relationship with the supplied power to operate the machine at a certain rotor speed.

Simultaneously, equation (15) reveals that the SPMSG’s voltage angle \( \Delta \theta \) is nonlinear and proportionately changing as a torque and rotor speed function. To create the requisite electromagnetic torque, the voltage angle \( \Delta \theta \) is required; as the rotor speed increases, so does the needed torque. So, the growing ratio becomes even more significant as the load power grows.

The proposed control technique delivers speed control without sensing the load current. This is accomplished by creating the dq-plane voltages required to supply the appropriate
power to keep the rotational speed constant. The current is indirectly regulated in this control strategy. Mainly, the power that SPMSG produces relies on the extracted current/voltage from the machine, which depends on the angular divergence between the machine’s terminal voltage and internal voltage. This reaction is reflected in the difference between the reference and actual speeds. Thus, by providing a decent control over the output voltage and its angle; the generated power and speed can be optimized. From maximum power point (MPP) equations, the optimum torque \( \tau_{\text{opt}} \) and speed \( \omega_{\text{opt}} \) can be brought about from (4) and (2) [34]. Therefore, equation (4) is used to retrieve the correct results of \( \tau \) instead of measuring the machine current or torque. It leads to a current sensorless controller. The voltage and its angle are expressed accordingly:

\[
v = p\omega_{\text{opt}} \sqrt{\frac{2L_q}{3p\lambda}} \tau_{\text{opt}}^2 + \lambda^2 + \Delta v
\]

where, \( \Delta v = K_p e_\omega + K_i \int e_\omega \)

To defeat unforeseen errors generated by approximations and converter nonlinearities and to solve the residual errors, a feedback controller is required. A closed-loop controller is also required to compensate for the mismatch between the actual rotor speed \( \omega \) and the reference value \( \omega_{\text{opt}} \) resulting from the electromagnetic torque. Thus, a speed tracking error \( e_\omega \) is defined as \( e_\omega = \omega_{\text{opt}} - \omega \). To reduce this deviation to zero, a PI controller is employed. The PI controller gains \( K_p \) and \( K_i \) are chosen through empirical analysis. Therefore, the PI controller uses the speed error as an indicator to provide the required voltage amplitude \( v \) deviation, for the reason that the linear relation between \( v \) and speed \( \omega \) as (14). Furthermore, since the voltage amplitude is controllable, the SPMSG can actually operate with MPE. It is notable that the MPE trajectory can be impacted if the PI controller is tuned inaccurately. However, since there is only one controller that compensates for residual errors, proper tuning of the controller is simple and painless. Finally, the control equation (16) is refined such that:

\[
v^* = p\omega_{\text{opt}} \sqrt{\frac{2L_q}{3p\lambda}} \tau_{\text{opt}}^2 + \lambda^2 + \Delta v
\]

Eventually, the desired control voltage amplitude \( v^* \) and angle \( \theta \), through Polar-Cartesian voltage transformation \( v_{\alpha}^* \) and \( v_{\beta}^* \) are applied to a sinusoidal PWM, as shown in Fig. 1. Further, Fig. 4 clarifies the proposed simplified MPE control technique, starting with the wind speed and ending with the inverter’s driving pulses in a flowchart form.

### III. SIMULATION AND EXPERIMENTAL INVESTIGATION ON SIMPLIFIED MPE CONTROL STRATEGY

#### A. SIMULATION RESULTS

The purpose of the advocated controller is extracting maximum power by minimizing copper loss despite wind velocity fluctuations. Fig. 5 demonstrates simulation results of the suggested method under wind velocity variations for 2.45MW wind turbine whose parameters are listed in Table 1 [35]. The reference wind velocity track is displayed in Fig. 5. It starts from zero until the nominal wind velocity of 13\( \text{m/s} \) at 18\( \text{s} \) the velocity declines gradually to 7\( \text{m/s} \), then it boosts again to 13\( \text{m/s} \) at 42\( \text{s} \).

It is shown in Fig. 5(b) that simplified MPE offers good speed tracking performance with acceptable deviations;
Besides, the FOC method is mentioned as a comparison strategy to assess the performance of the proposed method. It follows the optimum rotor speed calculated by MPP component of the proposed approach. The SPMSG is able to generate the required full power at the reference speed due to the voltage amplitude $v$ and angle $\Delta \theta$ compensation, as per Fig. 5(c) and 5(d). The mechanical and the electrical torques of the generator and the delivered power at the terminals considering wind velocity variations are provided in Fig. 5(e) and Fig. 5(f), respectively.

Remarkably, fluctuations in wind velocity and turbine mechanical torque cause fast changes in both the voltage amplitude $v$ and angle $\Delta \theta$. The suggested control technique is capable of responding quickly to unanticipated changes in turbine torque. This technique offers a smooth and speedy dynamical reaction since it directly controls the voltage vectors. The proportional correction of the $q$-axis voltage provides the required current for power generation to adjust the rotor speed instantly; therefore, the results clarify and prove the advantage of the proposed strategy.

Fig. 5 shows that the mechanical torque $T_m$, electrical torque $T_e$ and generated power $P_e$ increase in accordance with a rise in the wind velocity. The suggested approach adjusts the electromagnetic torque to ensure that the turbine extracts the maximum amount of power.

### B. HARDWARE SETUP

Experimental evaluations are implemented on a laboratory SPMSG setup along with a comparison against field-oriented control to confirm the efficacy of the introduced simplified MPE control strategy. In the proposed drive system, a high-level real-time emulator with a sample rate of 10kHz and
TABLE 2. System specification.

| SPMSG's Parameters       | Value       |
|--------------------------|-------------|
| Nominal power (W)        | $P_n = 300$ |
| Nominal speed (rpm)      | $w_m = 1500$|
| Nominal torque (N.m)     | $T_m = 2$   |
| Inductance on d-axis (H) | $L_d = 1.3 \times 10^{-4}$ |
| Inductance on q-axis (H) | $L_q = 1.3 \times 10^{-4}$ |
| Armature winding resistance (Ω) | $R = 1.9$ |
| Flux linkage (Wb)        | $\Lambda = 36.4 \times 10^{-3}$ |
| Static friction coefficient (N.m) | $F_r = 1.32 \times 10^{-3}$ |
| Rotor and load inertia (kg m²) | $J = 9 \times 10^{-6}$ |
| Number of pole pairs     | $p = 6$     |
| Wind turbine's Parameters| Value       |
| Nominal power (HP)       | $P_{hp} = 0.5$ |
| Nominal speed (rpm)      | $w_{hp} = 1750$ |
| Air density (kg/m³)      | $\rho = 1.2754$ |
| Tip speed ratio          | $\lambda_{tip} = 6.2836$ |
| Rotor power coefficient  | $C_p = 0.3125$ |
| Blade radius (m)         | $R_b = 0.6$  |

a duty cycle of $2kHz$ is used to operate the system. This emulator was created in the LabVIEW environment and is connected to a National Instruments PCI – 6225 card. As illustrated in Fig. 6, the card is placed to connect with a half-bridge chopper converter with a diode rectifier, which is utilized to drive a 300W, 1800rpm SPMSG. Pulsecoder of $5Vdc$ pulses generated and 600 (counts/rev) resolution measures the rotor position and speed. The attributes of the wind turbine are modeled by a DC motor emulator supervised using LabVolt/Festo drive and software. The wind velocity signal is applied by the SPMSG control system to manipulate the torque-speed command of the DC motor. The system specification of the SPMSG wind turbine are reported in Table 2.

C. EXPERIMENTAL VALIDATION

Several experimental investigations on an off-grid SPMSG-based WECS are carried out to validate the presented methodology. Fig. 6 shows the hardware setup and the supervision diagram. The experiment is followed up as the wind velocity changes from 3m/s to 12m/s through a 5 sec term for 1m/s increase, then declines to 7m/s during a time interval of 10 sec. Ultimately, the wind velocity is increased again to 14m/s, over the nominal wind velocity (12m/s), as Fig. 7(a). The behavior of the proposed simplified MPE under wind variations is shown in Fig. 7(b), 7(c), 7(d) and 7(e). The speed response of the SPMSG, as per Fig. 7(b), shows that this proposal brings maximum power extraction, minimum losses, and optimum speed tracking, despite wind velocity variations. The voltage amplitude $v$ and angle $\Delta \theta$ created for the SPMSG are presented in Fig. 7(c) and 7(d), computed by MPE tracking equations (17) and (18). The output power of the generator is presented in Fig. 7(e).

For a more profound analysis, experimental validation along with comparison against FOC MTPA used in [27] are put into execution once again with smooth wind velocity variations from 4m/s to 14m/s during 56 seconds depicted in Fig. 8(a). The rotor speed tracking performance for harvesting
maximum power can be found in Fig. 8(b), and the generated power is shown in Fig. 8(c).

The $P_e$ against $\omega_{opt}$ profile for various wind velocities obtained from experimental and FOC findings are overlaid on the $P_e$ vs $\omega$ characteristics supplied by the wind turbine manufacturer, as demonstrated in Fig. 8(d). Moreover, voltage regulation helps restricting the generated power to the maximum values, as exhibited in Fig. 7(e), 8(c), and 8(d). Additionally, the proposed control performance is quantified by calculating the root mean square error (RMSE) for rotor speed as Table 3.

### TABLE 3. Control performance quantify.

|        | RMSE 125kW | Simplified MPE | FOC    |
|--------|------------|----------------|--------|
| 360kW  | 1.4%       | 1.4%           | 0.9%   |
| 2.45MW | 2.1%       | 2.1%           | 1.7%   |

The results reveal that the suggested simplified MPE method has a slight deviation from the optimum speed as the FOC. Furthermore, the proposed control strategy yields around 0.5% error more than FOC in the extracted power under varying wind velocity. Eventually, the suggested control scheme can achieve MPE operation conditions with an acceptable error without the need for current regulation. This problem is attributed to the proposed method’s dynamic reaction during the startup phase. At the same time, the speed plots present good tracking for the proposed method and better accuracy in some parts.

### D. STATOR CURRENT STUDY

To further investigate the effectiveness of the current proposal, it is compared with the optimum current-voltage data of the manufacturer. It is reasonable to infer that the terminal voltage and delivered current of the generator are proportional to the rotor speed and torque of the turbine.

The obtained responses from the introduced MPE control approach and the manufacturer data are illustrated in Fig. 9. For this study, the wind velocity is between 4 m/s and 12 m/s. From Fig. 9, it is evident that although both approaches extract the same power, the stator current of the advocated model remains lower than the data provided by the manufacturer, at maximum power point (MPP). Accordingly, the electric power loss ($i^2R$) must be lower for the introduced model. Since MTPA is integrated into the suggested control method, the extraction of maximum power is ensured with minimum electrical power loss. Despite being a sensorless technique, it is observed that the introduced control method facilitates maximum power extraction for the generator with minimum copper losses and with a negligible speed drift, even under wind velocity fluctuations.
IV. CONCLUSION

The simplified current sensorless MPE control technique is developed for SPMSG-based variable speed WECS. The direct voltage command technique is practical for performing a simple MPE method unaccompanied by any current control loop. Also, being independent of the current measurement device reinforces the reliability of the system, especially, in the case of current sensor failure or noise. Using a single proportional controller leads to a straightforward tuning and execution process. The SPMSG generates the necessary electromagnetic torque to deliver maximum power at any wind velocity (above the cut-in speed) while consuming the minimum amount of stator current, thanks to the integration of the MPE technique and MTPA theory. Since it drives the SPMSG with a lower current, it minimizes active power losses in the stator windings. Therefore, the proposed simplified MPE technique guarantees maximum efficiency for the SPMSG-based WECS under wind velocity fluctuations. The performance of the developed technique is analyzed over few steps for various cases with simulations and real-time experimental trials of an off-grid surface-mount PMSG based WECS. Eventually, the results substantiate the effectiveness of the developed method in dynamic and steady-state operations. Besides, the simplified MPE control strategy can be considered an apposite candidate for low-cost solutions. Further, the proposed method is based on the steady-state model of SPMSG and does not take the ambient temperature variation into account. Thus, future work will try to include the dynamic parts of PMSG, generalize the control system for IPMSG/SPMSG, and consider the temperature as well.

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