A Novel Model Predictive Speed Controller for PMSG in Wind Energy Systems

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Abstract- In the present study, the machine-side converter (MSC) for a wind turbine (WT) system is controlled using a novel model predictive speed control (MPSC) technique. The proposed controller is employed to avoid the limitations associated with the cascaded structure of linear controllers. This MPSC is applied to the permanent magnet synchronous generator (PMSG). The novel MPSC is designed using a hybrid maximum power point tracking (MPPT) algorithm and this assists in capturing the maximum possible wind power. The proposed control technique allows for controlling both electrical and mechanical variables simultaneously within a single control loop. As a result, the conventional cascaded structure of proportional-integral (PI) controllers is eliminated, which enhances the system dynamic response. As the suggested MPSC is a model-based control strategy; therefore, its performance is evaluated under various PMSG parameters. In the grid-side converter (GSC), a model predictive current control (MPCC) approach is employed in order to achieve active and reactive power control. This is accomplished by controlling the grid currents in a decoupled manner. A complete model of the WT system with direct-driven PMSG is conducted using MATLAB/Simulink. The proposed MPSC performance is investigated. Moreover, its performance is compared with a classical PI speed controller under various wind conditions. Based on the simulation results, it is indicated that model predictive control (MPC) outperforms the PI controller in handling the system dynamics. The system efficiency using the suggested MPSC is about 94.5 % at rated wind speed. The novel MPSC shows a good performance for several PMSG parameters.

Keywords PMSG; MPPT; Wind energy; Model predictive control (MPC); Speed Controller.

1. Introduction

The integration of renewable sources of energy into the electrical grid has gained more attention globally [1–4]. Among the different forms of renewables, wind energy is observed to have a rapid growing rate in the electricity market [5–7]. A substantial share of electricity in several countries is provided by wind power. In 2020, a wind power capacity of about 93 GW was installed globally [8]. Through the global wind energy markets, several wind energy conversion systems (WECS) have been formed and these can be classified into 4 types [9]. The conversion efficiency of Type 4 is the highest among these types of WECS [10]. Type 4 wind energy system offers the advantage of achieving full variable-speed operation; therefore, maximum available power at different wind speeds can be obtained [11]. The permanent magnet synchronous generator (PMSG) is considered as the most recommended choice in the case of Type 4 WECS. This is due to: (i) elimination of dc excitation system, (ii) lower rotor losses, (iii) gearless operation, (iv) less maintenance required and high efficiency [12–14].

Because of the stochastic nature of the wind, it is very important to maximize the energy yield in variable-speed WECS (VS-WECS). Maximum power point tracking (MPPT) techniques are considered to be essential for ensuring the maximum wind power extraction [15]. The most widely utilized techniques for MPPT in wind turbine (WT) systems are the optimal torque (OT) and the optimal tip speed ratio (TSR) control methods, which offer the best trade-off between the complexity and the performance during variable wind speeds [12, 13, 16–20].

In order to achieve the accurate control and the desired operation of VS-WECS with PMSG, several strategies have been implemented. The voltage-oriented control (VOC) and field-oriented control (FOC) strategies are considered as the most popular linear control methods for grid-side converters (GSCs) and machine-side converters (MSCs), respectively.

These control schemes use a structure of cascade control loops, including PI controllers in the internal and external control loops along with the pulse width modulation (PWM) scheme in order to generate the required switching signals for the power converters [20–27]. The FOC scheme combines a slow outer speed control loop with fast inner current control loops. In addition, the current control loops are implemented in a synchronously rotating *dq* frame for controlling the generator currents in a decoupled manner, while the outer speed loop is responsible for regulating the generator speed for different reference values. The VOC scheme consists of an outer control loop for DC-link voltage to maintain its reference value. Furthermore, the inner current control loops are implemented to inject the active power from the PMSG to the grid at unity power factor (UPF) [28, 29]. However, classical linear control methods have many drawbacks. For example, the linear controller transient response strongly depends on the tuning of many gain values in the PI cascaded control structure. Control variables such as *dq*-axes generator or grid currents exhibit noticeable coupling effects; therefore, decoupling of *dq* components of the current requires additional feed-forward terms with higher control complexity. Steady-state performance depends on the nature of control variables, where it is good only in the *dq*-axes reference frame. Dynamic performance is moderate and others can be found in [30–33]. Owing to the rapid evolution in microprocessors, more advanced control techniques are now achievable to attain optimal system performance.

Finite-control-set model predictive control (FCS-MPC) is considered as one of the advanced control schemes that offers several key features which enable it to be appropriate for power converters control [30, 34–37]. For instance, it is a simple control technique that can be implemented in various systems and can disuse the modulation scheme. Further, it features a rapid dynamic performance in contrast with the linear controllers. Due to the fact that the number of power converter switching states is finite, the FCS-MPC utilizes a discrete-time (DT) model for predicting the behavior of the variables under control for all switching states. Then, evaluating a cost function using the predicted variables, and consequently, the optimum switching signals which minimize the cost function are determined. After that, the selected switching signals are directly sent to the power converter control unit [32, 35, 36]. In Type 4 WECS, the operating principles of FOC scheme have been used by FCS-MPC to design model predictive current control (MPCC) technique for PMSG by only eliminating the inner PI current control loops, which improves the dynamic response [13, 18, 38, 39]. However, it still employs cascaded control loops along with a PI speed regulator as well as the dynamic response of the external speed controller can be enhanced. In [29], the outer PI speed controller is replaced by a MPC scheme, while the inner one is used for controlling the current through a classical hysteresis controller. Using the suggested MPC, the overall system efficiency is increased to 95.12 percent. However, the cascaded control structure still exists in the MSC control scheme. To design a straightforward control structure and avoid the tedious process of tuning PI controller parameters, MPC allows to include different variables into a single multi-term cost function without employing the cascaded control structure or any external PI speed control loop. In [35, 40–44], a model predictive speed control (MPSC) technique is applied on the permanent magnet synchronous motor, allowing for simultaneous manipulation of the speed and currents in a single objective function. In [45], a MPSC scheme for PMSG in a WT system has been proposed. The dynamic response of the rotor speed has been improved using the proposed speed controller, with no overshoot in the mechanical speed and a 45.5 percent reduction in settling time. However, the control method implementation has not taken into consideration the wind energy system characteristics.

In this paper, a novel MPSC strategy with a cascade-free control structure is proposed for PMSG in the VSWT system. The proposed MPSC allows controlling the mechanical speed and electrical variables in a single control loop. A hybrid MPPT algorithm is employed to design a multi-objective function for identifying the best switching state without using any PWM stage. The suggested control technique is simple and takes into account the characteristics of WT systems. Furthermore, since the proposed MPSC is a model-based control technique, its behavior is also assessed under variations of PMSG parameters. To assess the efficacy of the suggested MPSC approach, its performance under different wind speeds is compared against the performance of the selected controller. The selected controller combines an outer-loop PI speed controller and an inner-loop MPCC. The PI controller parameters are adjusted based on the rules described in [21, 46]. The MPCC scheme is applied to the GSC to deliver the real power into the grid at UPF. This paper presents the following main contributions:

1. Designing a novel MPSC strategy with a cascade-free control structure for the MSC by incorporating the electrical and mechanical variables into a single control loop.
2. The novel MPSC strategy is designed using a hybrid MPPT method to trace and capture the maximum power of the VSWT system.
3. The behavior of the proposed MPSC is also emphasized for various PMSG parameters.
4. Comparative assessment is carried out between the proposed MPSC and the classical speed controller to show the efficacy of the suggested strategy for wind speed change.
5. The MPCC has been applied to the GSC as a replacement of the inner PI current control loop.

2. Wind Energy System Model

The entire configuration of the VSWT system with direct-driven PMSG is depicted in Fig.1. The back-to-back (BTB) power converters are realized by the MSC and GSC that are linked by a DC-link. The generator output power and its rotational speed are regulated using MSC. On the other hand, the GSC is responsible for controlling the reactive power as well as the DC-link voltage.

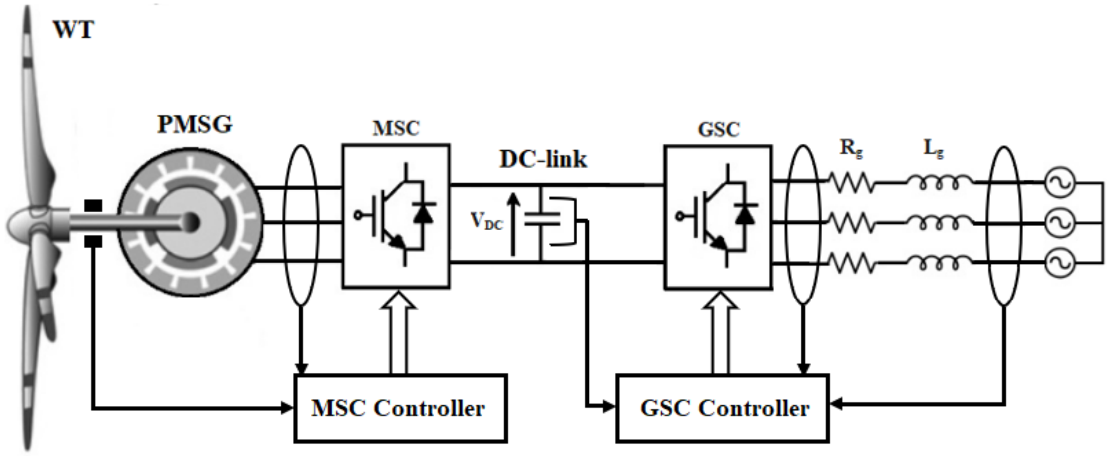


Fig. 1. A schematic diagram for the WT System based on direct-driven PMSG.

2.1. Wind Turbine Model

In the WT systems, the mechanical power could be expressed as follows [47, 48]:

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) {V_w}^3 \quad (1)$$

where A is area swept by the WT blades, V_w is the wind speed, ρ is the air density, C_p is the power coefficient of the WT that is a function of the blade pitch angle (β) and the TSR (λ). The TSR is an essential parameter of the WT and can be formulated by Eq. (2):

$$\lambda = \frac{\omega_m R}{V_w} \quad (2)$$

where R is the length of the blade, ω_m is the rotational speed of the turbine rotor.

In this paper, the C_p value can be calculated from Eqs. (3) and (4) [49]:

$$C_p(\lambda, \beta) = C_{t1}\left(\frac{C_{t2}}{\lambda_i} - C_{t3}\beta - C_{t4}\right) e^{\frac{-C_{t5}}{\lambda_i}} + C_{t6}\lambda \quad (3)$$

$$\frac{1.0}{\lambda_i} = \frac{1.0}{\lambda + 0.08 \times \beta} - \frac{0.035}{1 + (\beta)^3} \quad (4)$$

Fig. 2 illustrates the relation between C_p and TSR at zero pitch angle. Continuous operation of the WT at λ_{opt}, where C_p is maximum, ensures that the maximum power will be captured at any wind speed [16].

The WT mechanical torque is defined by:

$$T_m = \frac{P_m}{\omega_m} \quad (5)$$

2.2. PMSG dynamic Model

The permanent magnet synchronous (PMS) machines may operate into either motor or generator modes by simply altering the sign of shaft mechanical torque T_m. In WECS, the T_m has a negative sign and the PMS machine works as a generator [30]. The three-phase PMSG mathematical model could be expressed in dq-axes frame as follows [38]:

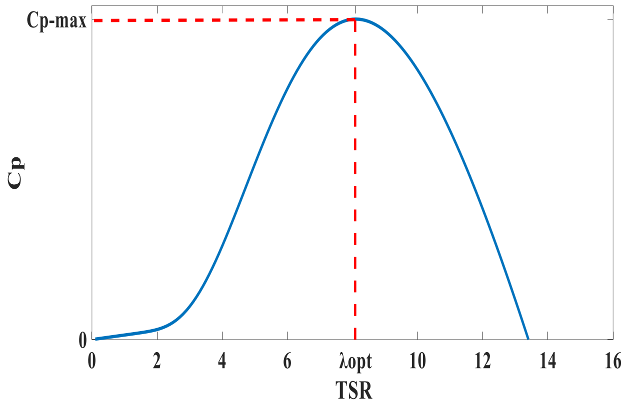


Fig. 2. C_p versus TSR curve

$$\left.\begin{aligned} v_{ds} &= R_s i_{ds} + L_d \frac{d}{dt} i_{ds} - \omega_r L_q i_{qs} \\ v_{qs} &= R_s i_{qs} + L_q \frac{d}{dt} i_{qs} + \omega_r L_d i_{ds} + \omega_r \psi_r \end{aligned}\right\} \quad (6)$$

where L_d and L_q are the dq-axes stator inductances, R_s denotes the stator winding resistance, i_{ds} and i_{qs} are the dq-axes stator currents, ω_r denotes the generator angular speed, ψ_r denotes the permanent magnet flux linkage.

The PMSG electromagnetic torque T_e is:

$$T_e = \frac{3}{2} P_p [\psi_r i_{qs} + (L_d - L_q) i_{ds} i_{qs}] \quad (7)$$

where P_p is the pole pairs number. For $L_d = L_q = L_s$, in the surface mounted PMSG (SPMSG), the electromagnetic torque in Eq. (7) may be rewritten as follows:

$$T_e = \frac{3}{2} P_p \psi_r i_{qs} \quad (8)$$

The equation of rotor speed dynamics can be expressed by:

$$J \frac{d}{dt}\omega_m + F\omega_m = T_e - T_m \quad (9)$$

where J denotes the moment of inertia, ω_m is the mechanical angular speed of the generator, and F denotes the friction coefficient.

The following equation describes the relation between the electrical and mechanical angular speed:

$$\omega_r = P_p \omega_m \tag{10}$$

From Eq. (9), it is clear that the mechanical speed of the generator may be controlled by the electromagnetic torque. In addition, because of the constant value of ψ_r of PMSG in Eq. (8), the q-axis component of stator current can be used directly to regulate the electromagnetic torque. Hence, the control of the generator rotational speed is achieved by the q-axis stator current component of PMSG. The d-axis stator current component is set to zero to implement zero direct-axis current (ZDC) technique in order to control the SPMSG [20, 22, 39].

3. Finite-Control-Set Model Predictive Control

The explicit use of the system models to predict the future behavior of the variables under control is the main feature of FCS-MPC. Since a power converter can only generate switching states with a limited number, the discrete model is employed to predict the future values of each controlled variable for every switching state. The desired behavior of the system is associated with minimizing the cost function. The switching state that minimizes the cost function is determined and applied to the converter without using a modulation technique [35, 36]. In the present work, the FCS-MPC approach is employed in order to design the novel MPSC strategy at MSC. In addition, it is applied to control grid currents instead of PI current controllers in the inner loop at GSC, whereas the DC-link voltage is regulated using the outer loop via a PI controller.

3.1. Proposed Model Predictive Speed Control for MSC

Fig. 3 illustrates the schematic representation of the novel MPSC. To design the proposed MPSC scheme, the SPMSG continuous-time (CT) model must be discretized in order to obtain the predictive model of the system. This model is then utilized for predicting the system variables' behavior in the next sampling instant. The stator current dynamics of SPMSG in dq frame are acquired from Eq. (6) as follows:

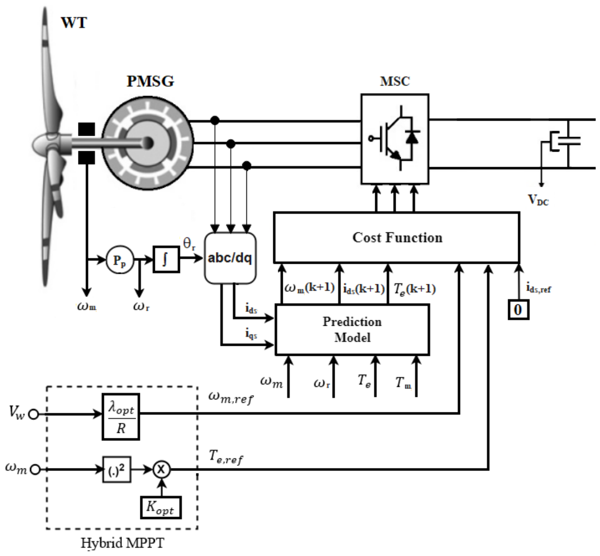


Fig. 3. Block diagram of novel MPSC for PMSG in VSWT system.

$$\left.\begin{aligned} \frac{d}{dt} i_{ds} &= -\frac{R_s}{L_s} i_{ds} + \omega_r i_{qs} + \frac{1}{L_s} v_{ds} \\ \frac{d}{dt} i_{qs} &= -\frac{R_s}{L_s} i_{qs} - \omega_r i_{ds} + \frac{1}{L_s} v_{qs} - \frac{\omega_r \psi_r}{L_s} \end{aligned}\right\} \tag{11}$$

Using forward Euler (FE) approximation method, Eqs. (9) and (11) can be discretized to obtain the predicted generator mechanical speed and the stator currents values as follows:

$$i_{ds}(k+1) = \omega_r(k) T_s i_{qs}(k) + \left(1.0 - \frac{R_s T_s}{L_s}\right) i_{ds}(k) + \frac{T_s}{L_s} v_{ds}(k) \tag{12}$$

$$i_{qs}(k+1) = -\omega_r(k) T_s i_{ds}(k) + \left(1.0 - \frac{R_s T_s}{L_s}\right) i_{qs}(k) + \frac{T_s}{L_s} v_{qs}(k) - \frac{\omega_r(k)\psi_r T_s}{L_s} \tag{13}$$

$$\omega_m(k+1) = \frac{T_s}{J}\big(T_e(k+1) - T_m(k)\big) + \omega_m(k) \tag{14}$$

where T_s is the sampling time.

$T_e(k+1)$ in Eq. (14) can be expressed by:

$$T_e(k+1) = \frac{3}{2} P_p \psi_r i_{qs}(k+1) \tag{15}$$

The proposed MPSC scheme directly controls the electrical and mechanical variables in a single control loop. Using the seven different possible switching states combinations of 2L-VSC, seven different values for v_{ds} and v_{qs} can be obtained. These values are used by the predictive models in Eqs. (12), (13) and (14) to obtain seven different values for i_{ds} (k + 1), i_{qs} (k + 1) as well as ω_m (k + 1). At the final stage, using the predicted values, a cost function is computed for the seven states, and the optimum switching signals are sent to the MSC control unit. To design the proposed cost function, it is very important to compute the reference values of the generator mechanical speed $\omega_{m,ref}$ and the electromagnetic torque $T_{e,ref}$. These values can be obtained using a hybrid MPPT technique as depicted in Fig.3. The $\omega_{m,ref}$ can be computed using the optimal TSR MPPT algorithm as in Eq. (16) while the $T_{e,ref}$ can be calculated through the OT MPPT algorithm as given in Eq. (17) [16, 17].

$$\omega_{m,ref} = \frac{\lambda_{opt} V_w}{R} \tag{16}$$

$$T_{e,ref} = \frac{1}{2}\rho\pi R^5 \frac{C_{p-max}}{\lambda_{opt}^3}\omega_m^2 = K_{opt}\,\omega_m^2 \tag{17}$$

The cost function of the novel MPSC is formulated as:

$$g_M = \frac{|\omega_{m,ref} - \omega_m(k+1)|}{\omega_{m,rated}} + \frac{|i_{ds,ref} - i_{ds}(k+1)|}{I_s} + \frac{|T_{e,ref} - T_e(k+1)|}{T_{e,rated}} + g_c \tag{18}$$

where:

$$g_c = \begin{cases} \infty, \; if \; \sqrt{i_{ds}(k+1)^2 + i_{qs}(k+1)^2} > i_s \\ 0, \; otherwise \end{cases} + \begin{cases} \infty, \; if \; \omega_m(k+1) > \omega_{m,rated} \\ 0, \; otherwise \end{cases} \quad (19)$$

The controlled variables in the designed multi-term cost function have different physical natures. A well-known solution for overcoming this issue is to normalize the error terms in the cost function [33, 50, 51]. The speed term of g_M is responsible for tracking mechanical reference speed determined using the optimal TSR technique. The current term is used to achieve the ZDC control technique for SPMSG by setting $i_{ds,ref}$ equal to zero. The torque term is responsible for regulating the electromagnetic torque with its reference value calculated using the OT method. Therefore, in steady-state, T_e and T_m coincide well, and the final term is a constrained term that equals zero in normal conditions and infinity when exceeding the rated values of the stator current amplitude or mechanical speed (i.e., i_s or $\omega_{m,rated}$). The voltage vectors that result in a quite high value of the objective function will not be chosen. Fig. 4 describes the flowchart of the suggested MPSC algorithm.

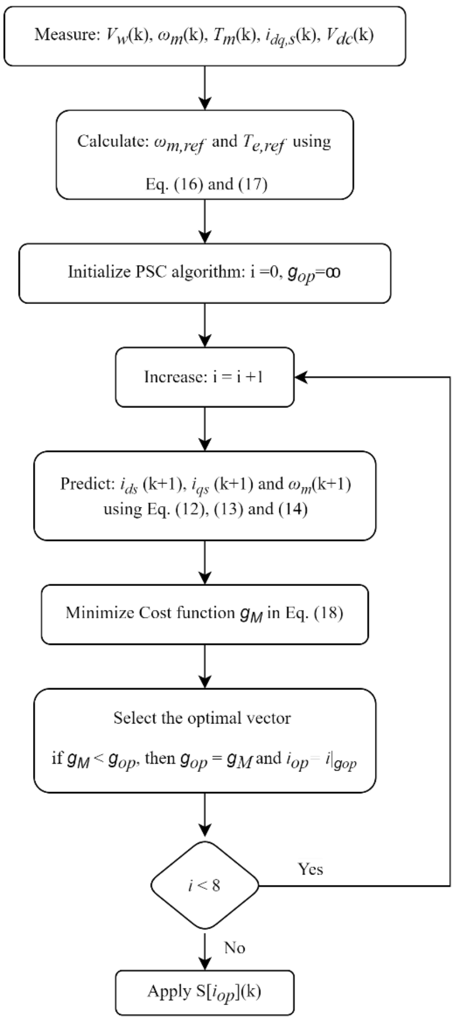


Fig. 4. Flowchart for 2L-VSC proposed MPSC algorithm.

3.2. Model Predictive Current Control for GSC

The MPCC technique is applied for GSC to control the power supplied to the electrical utility grid as illustrated in Fig.5. The GSC voltages in *dq* frame are formulated by:

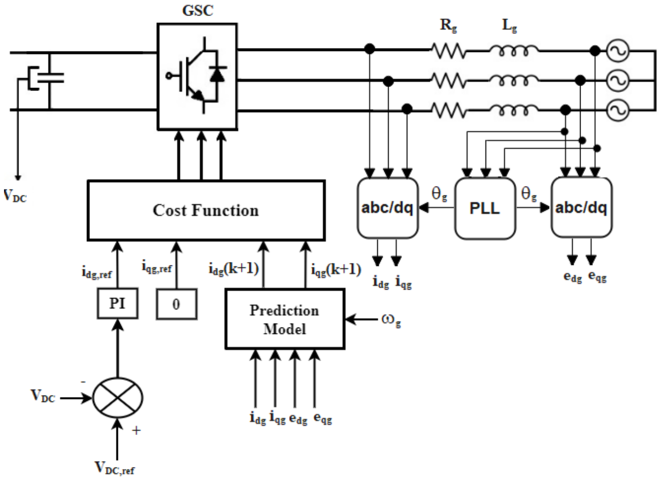


Fig. 5. The MPCC schematic diagram.

$$\left.\begin{aligned} v_{dg} &= R_g i_{dg} + L_g \frac{d}{dt} i_{dg} - \omega_g L_g i_{qg} + e_{dg} \\ v_{qg} &= R_g i_{qg} + L_g \frac{d}{dt} i_{qg} + \omega_g L_g i_{dg} + e_{qg} \end{aligned}\right\} \quad (20)$$

where ω_g denotes the angular frequency of the grid, i_{dg} & i_{qg} represent the *dq* grid currents, L_g & R_g indicate the grid filter inductance & resistance, e_{dg} & e_{qg} represent the *dq* grid voltages. By applying the FE method to Eq. (20), the DT model of grid currents is given by:

$$i_{dg}(k+1) = \omega_g T_s i_{qg}(k) + \left(1 - \frac{R_g T_s}{L_g}\right) i_{dg}(k) + \frac{T_s}{L_g}\left(v_{dg}(k) - e_{dg}(k)\right) \quad (21)$$

$$i_{qg}(k+1) = -\omega_g T_s i_{dg}(k) + \left(1 - \frac{R_g T_s}{L_g}\right) i_{qg}(k) + \frac{T_s}{L_g}\left(v_{qg}(k) - e_{qg}(k)\right) \quad (22)$$

The cost function designed for the GSC is formulated as:

$$g_G = \left|i_{dg,ref} - i_{dg}(k+1)\right| + \left|i_{qg,ref} - i_{qg}(k+1)\right| + \begin{cases} \infty, \; if \; \sqrt{i_{dg}(k+1)^2 + i_{qg}(k+1)^2} > i_g \\ 0, \; otherwise \end{cases} \quad (23)$$

The cost function of the GSC aims at declining the difference between the predicted and reference values of *dq*-axes grid currents, with a constrained term that allows grid current limitation by avoiding the voltage vectors that cause the grid current to exceed its rated value (i.e., i_g). The outer PI controller of the DC-link voltage generates the value of the $i_{dg,ref}$, while the $i_{qg,ref}$ is adjusted at zero in order to inject zero reactive power into the grid.

Similar to the steps applied for the MSC, the DT model in Eqs. (21) and (22) is utilized to predict the next values of the i_{dg} (k + 1) & the i_{qg} (k + 1) for all different switching state combinations of 2L-VSC. The predicted grid currents are then assessed via Eq. (23) to select the GSC optimum switching signals, which leads to a reduction in the cost function.

4. Simulation Results

A MATLAB/SIMULINK model is constructed to study and verify the proposed control scheme performance when applied to a VSWT system with direct-driven PMSG. The simulation is conducted based on the system parameters specified in Tables 1 & 2. The simulation tests are carried out under two case studies. The first case assumes variable wind speeds, and the dynamic response of the suggested MPSC is evaluated against the classical PI speed controller for MSC control. The second case assumes changing the PMSG parameters in the software model, and the performance of the MPSC is investigated under these variations.

4.1. Case (1): variable wind speed profile

Figs. 6 (a) & (b) illustrate the WT characteristics using the proposed MPSC approach and classical PI speed controller, respectively, under varying wind speeds over 0.5s time span. By comparing the simulation results at wind speed transitions, the system dynamic response is improved using the proposed MPSC. Furthermore, the mechanical power, using the proposed MPSC, reaches its theoretical value at rated wind speed approximately 4 ms faster than the PI speed controller.

Fig. 7 displays the ability of the speed controllers to track PMSG mechanical speed reference value, which ensures capturing the maximum power at various wind speeds. The mechanical rotor speed exhibits no overshoot using the proposed MPSC, while an overshoot of about 33.8 % exists in the generator speed using the PI speed controller when wind speed changes to the rated value at 0.2s. Furthermore, using the proposed MPSC, the settling time (5 percent tolerance band) is 6.8 ms, whereas using a PI speed controller, the settling time is 11.2 ms. The electromagnetic torque T_e tracks the mechanical torque T_m. However, the dynamic response of T_e using the MPSC strategy outperforms the classical one with wind speed variations. The corresponding change in PMSG currents can be also observed. The phase-a stator current and *dq*-axes current components track changes in wind speed. Using the proposed MPSC technique, the magnitude and frequency of phase-a stator current vary smoothly with the PMSG mechanical speed. The *d*-axis current component is kept constant at zero, whilst the *q*-axis stator current changes linearly with the T_e. Evidently, the *dq*-axes stator currents are controlled in a decoupled pattern.

The results of the GSC control using the proposed overall control scheme are represented in Fig.8. As can be observed, the DC-link voltage is successfully maintained at its reference value with a tiny overshoot and dip during the wind speed variations. The system operates at UPF by injecting zero VAR into the grid. Wind speed variations have a direct impact on real power supplied to the electrical utility grid via the GSC. The *d*-axis grid current tracks the injected real power, and the *q*-axis current is usually forced to zero to supply zero VAR to the electrical utility grid. The grid current and voltage are in-phase, achieving UPF operation. The overall VSWT system efficiency using the proposed strategy is about 94.5 % at rated wind speed.

4.2. Case (2): Effect of PMSG parameter variations

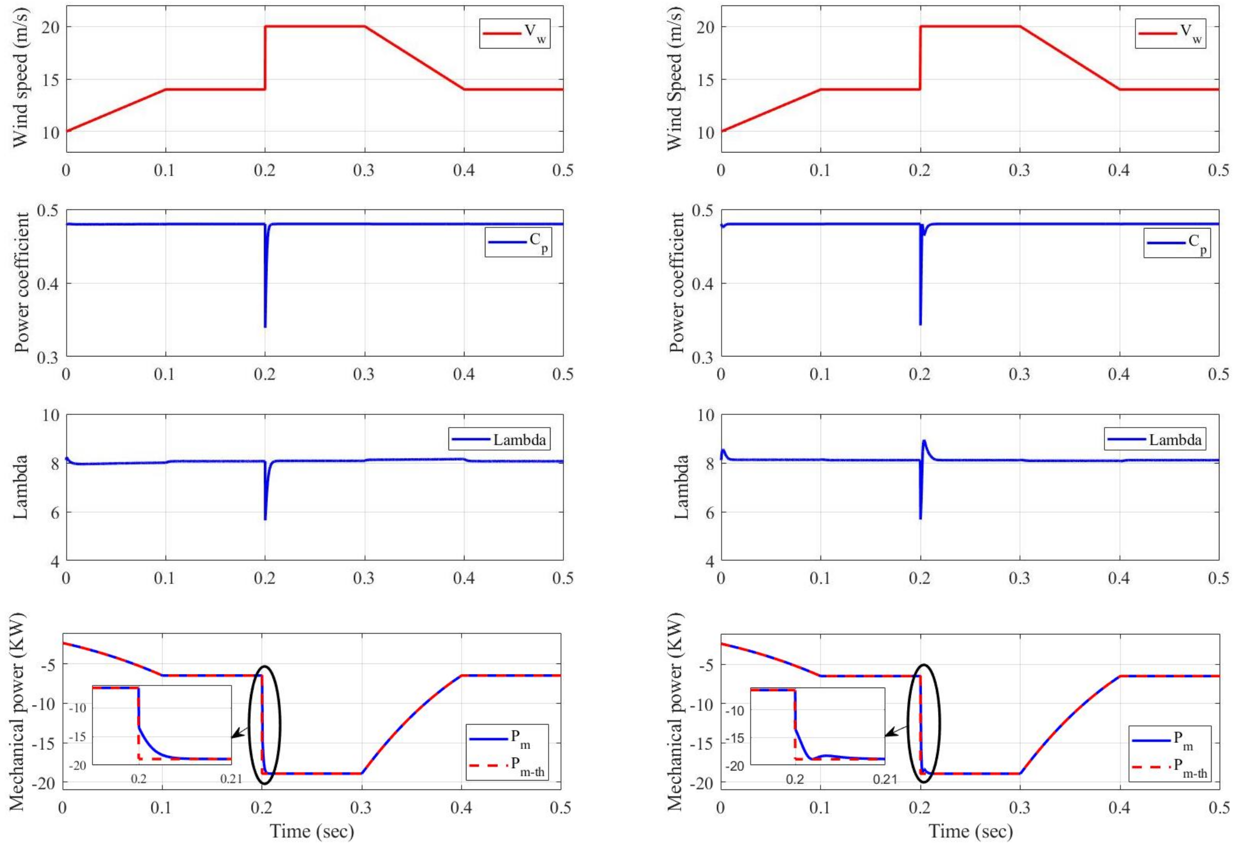
Since the proposed MPSC is a model-based control strategy, it is important to show how the novel MPSC behaves in the presence of variations in the machine parameters. The MPSC performance is examined for $\mp 50\%$ changes in the stator inductance & resistance of the PMSG at t = 0.5s & t = 1.5s, respectively. The simulation results are conducted under parameter variability with an 18 m/s fixed wind speed. As shown in Fig.9 (a), the suggested MPSC technique is to some extent sensitive to stator inductance L_s variations. It is visible that there are slightly higher ripples manifest in the electromagnetic torque and *dq*-axes stator currents waveforms due to the inductance variation at t = 0.5s. The response of the generator mechanical speed is also still acceptable. Fig. 9 (b) clarifies that there is no impact on the performance of the suggested MPSC in the presence of variations in the stator resistance.

Table 1. System parameters [52]

Parameter	Symbol	Value
Blade radius	R	1.6 m
Maximum power coefficient	C_p	0.48
Optimal TSR	λ_{opt}	8.11
Rated wind speed	V_w	20 m/s
WT coefficients	C_{t1}	0.5176
	C_{t2}	116
	C_{t3}	0.4
	C_{t4}	5
	C_{t5}	21
	C_{t6}	0.0068
PMSG RMS line voltage	V_s	400 V
Stator inductance	L_s	15 mH
Stator resistance	R_s	0.2 Ω
Pole pairs number	P_p	3
Permanent magnet flux linkage	ψ_r	0.85 Wb
Moment of inertia	J	0.01 $Kg.m^2$
Sampling time	T_s	15 µs
Capacitor of the DC-link	C	3 mF
DC-link voltage	V_{dc}	700 V
Grid resistance	R_g	0.16 Ω
Grid inductance	L_g	10 mH
Grid frequency	f	50 Hz

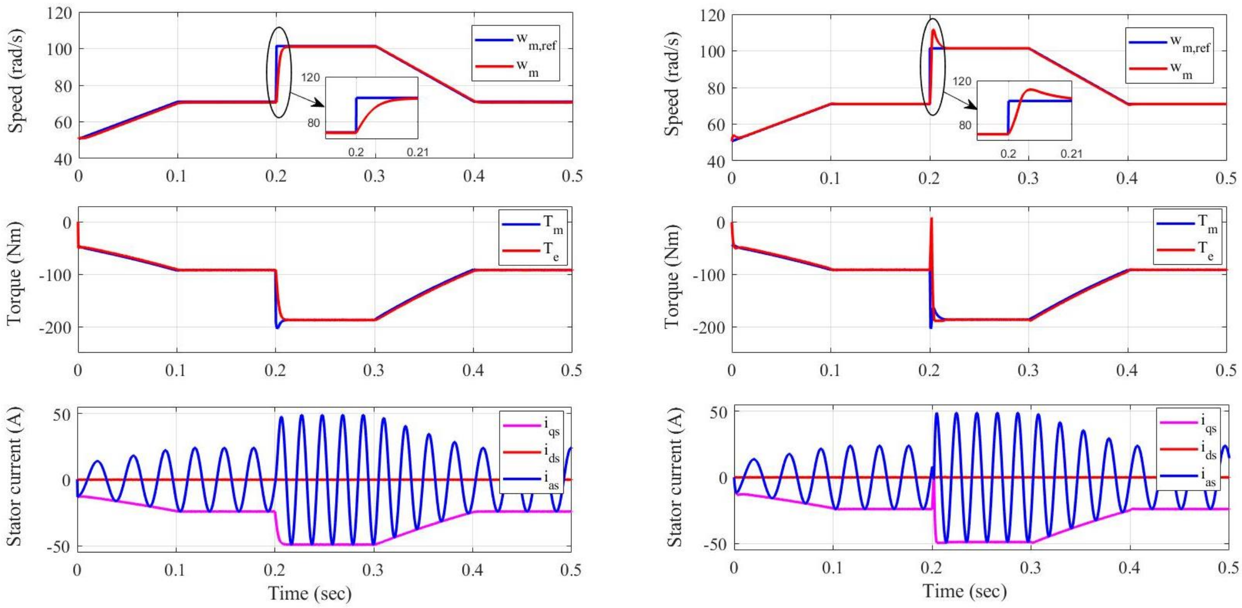
Table 2. PI speed controller parameters

Parameter	Value
K_p	10.47
T_i	0.0029



(a) (b)

Fig. 6. The WT characteristics: (a) Proposed MPSC, and (b) PI speed controller.



(a) (b)

Fig. 7. The MSC control results: (a) Proposed MPSC, and (b) PI speed controller.

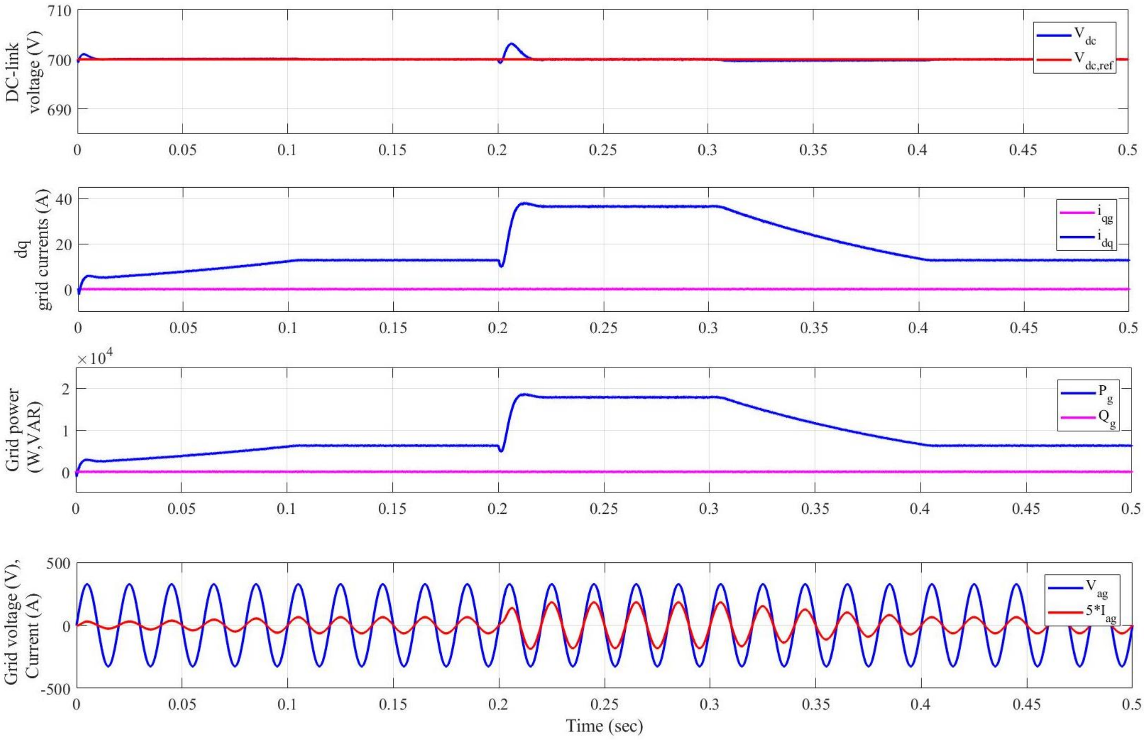


Fig. 8. The GSC control results.

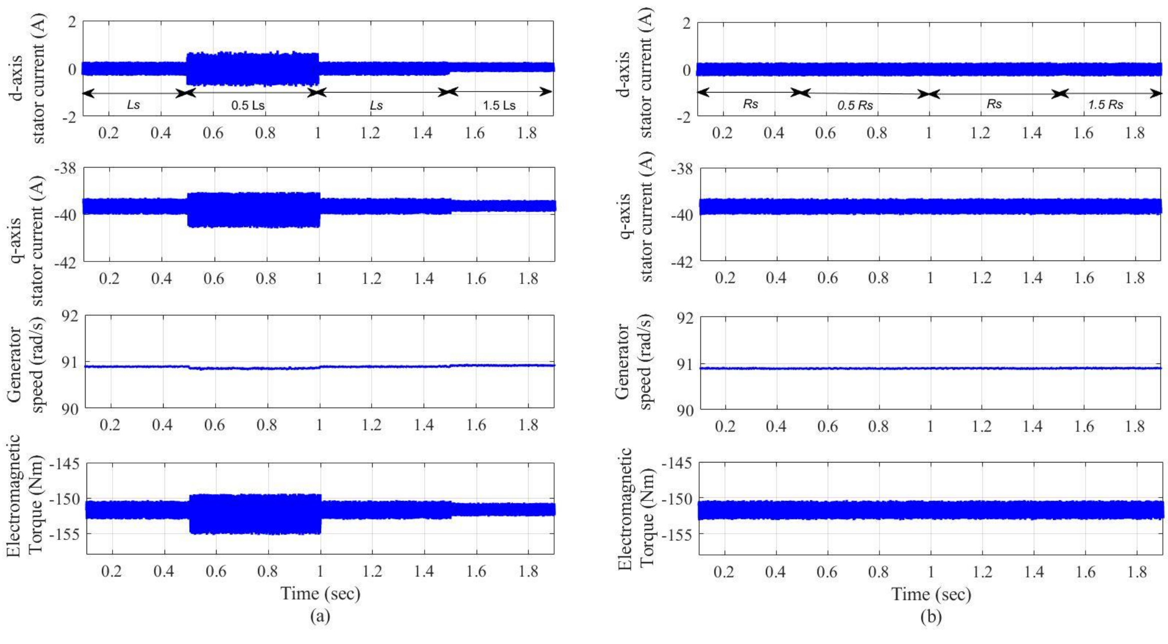


Fig. 9. The MPSC results under variability of PMSG: (a) inductance L_s, (b) resistance R_s

5. Conclusion

A novel MPSC strategy of the MSC in VSWT system with direct-driven PMSG has been presented. The proposed strategy adopted a cascade-free control structure; therefore, the conventional cascaded structure of PI controllers and the PWM stage are no longer existed. The new control technique employed a hybrid MPPT algorithm to maximize the power yield in the WT system. Furthermore, a MPCC was used instead of the PI current controller for the GSC in order to control the injected power into the electrical utility grid. MATLAB simulations have been performed to assess the system performance under different wind speeds. A comparative analysis has been conducted between the novel MPSC strategy and the PI as speed controller. The results showed that the novel MPSC has a smooth operation and fast dynamic response with no overshoot in the MSC control results compared with conventional PI controller under wind speed variations. The overall efficiency using the suggested speed controller is about 94.5% at rated wind speed. In addition, the influence of PMSG parameters variations on the steady-state behavior of the MPSC technique has been investigated. The MPSC showed satisfactory results under variations of the machine inductance and the effect of the resistance variations can be ignored.

References

[1] A. Refaat, M. H. Osman and N. V Korovkin, "Current collector optimizer topology to extract maximum power from non-uniform aged PV array," Energy, vol. 195, p. 116995, March 2020.

[2] A. AlKassem, M. Al Ahmadi and A. Draou, "Modeling and Simulation Analysis of a Hybrid PV-Wind Renewable Energy Sources for a Micro-Grid Application," in 2021 9th International Conference on Smart Grid (icSmartGrid), Setubal, pp. 103–106, June 2021.

[3] A. Refaat and N. Korovkin, "A new photovoltaic current collector optimizer to enhance the performance of centralized inverter topologies," in Advances in Intelligent Systems and Computing, vol. 982, pp. 216–224, 2020.

[4] A. Refaat, M. Elgamal and N. V Korovkin, "A novel photovoltaic current collector optimizer to extract maximum power during partial shading or mismatch conditions," in 2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), Saint Petersburg, pp. 407–412, January 2019.

[5] Y. Elhenawy, Y. Fouad, H. Marouani and M. Bassyouni, "Performance analysis of reinforced epoxy functionalized carbon nanotubes composites for vertical axis wind turbine blade," Polymers, vol. 13, No. 3, p 422, January 2021.

[6] M. M. Elsakka, D. B. Ingham, L. Ma and M. Pourkashanian, "Effects of turbulence modelling on the predictions of the pressure distribution around the wing of a small scale vertical axis wind turbine," in Proceedings of the 6th European Conference on Computational Mechanics: Solids, Structures and Coupled Problems, ECCM 2018 and 7th European Conference on Computational Fluid Dynamics, ECFD 2018, 2020, pp. 3921–3931.

[7] M. M. Elsakka, D. B. Ingham, L. Ma and M. Pourkashanian, "Comparison of the Computational Fluid Dynamics Predictions of Vertical Axis Wind Turbine Performance Against Detailed Pressure Measurements," International Journal of Renewable Energy Research, vol. 11, No. 1, pp. 276–293, March 2021.

[8] GWEC, Global Wind Report 2021, Global Wind Energy Council, available at: https://gwec.net/global-wind-report-2021/accessed on 10 February 2022.

[9] H. Zhao and Q. Wu, Modeling and Modern Control of Wind Power, John Wiley & Sons, Ltd, 2018, ch. 1.

[10] V. Yaramasu, B. Wu, P. C. Sen, S. Kouro and M. Narimani, "High-power wind energy conversion systems: State-of-the-art and emerging technologies," Proceedings of the IEEE, vol. 103, No. 5, pp. 740–788, May 2015.

[11] Y. Errami, M. Ouassaid and M. Maaroufi, "Control of a PMSG based wind energy generation system for power maximization and grid fault conditions," Energy Procedia, vol. 42, pp. 220–229, 2013.

[12] V. Yaramasu, A. Dekka, M. J. Durán, S. Kouro and B. Wu, "PMSG-based wind energy conversion systems: survey on power converters and controls," IET Electric Power Applications, vol. 11, No. 6, pp. 956–968, July 2017.

[13] V. Yaramasu, S. Kouro, A. Dekka, S. Alepuz, J. Rodriguez and M. Duran, "Power conversion and predictive control of wind energy conversion systems," in Advanced Control and Optimization Paradigms for Wind Energy Systems, Springer, pp. 113–139, 2019.

[14] Y. E. A. Eldahab, N. H. Saad and A. Zekry, "Assessing Wind Energy Conversion Systems Based on Newly Developed Wind Turbine Emulator," International Journal of Smart Grid-ijSmartGrid, vol. 4, No. 4, December 2020.

[15] I. Grgić, M. Bašić, D. Vukadinović and M. Bubalo, "Optimal Control of a Standalone Wind-Solar-Battery Power System with a Quasi-Z-Source Inverter," in 2020 9th International Conference on Renewable Energy Research and Application (ICRERA), Glasgow, pp. 61–66, September 2020.

[16] M. A. Abdullah, A. H. M. Yatim, C. W. Tan and R. Saidur, "A review of maximum power point tracking algorithms for wind energy systems," Renewable and sustainable energy reviews, vol. 16, No. 5, pp. 3220–3227, June 2012.

[17] D. Kumar and K. Chatterjee, "A review of conventional and advanced MPPT algorithms for wind energy systems," Renewable and sustainable energy reviews, vol. 55, pp. 957–970, March 2016.

[18] M. Abdelrahem, C. Hackl and R. Kennel, "Model predictive control of permanent magnet synchronous generators in variable-speed wind turbine systems," Proceedings of Power and Energy Student Summit (PESS 2016), 2016.

[19] H. H. H. Mousa, A.-R. Youssef and E. E. M. Mohamed, "Model predictive speed control of five-phase PMSG based variable speed wind generation system," in 2018 Twentieth international middle east power systems conference (MEPCON), Cairo, pp. 304–309, Dec. 2018.

[20] D. K. Porate, S. P. Gawande, A. P. Munshi, K. B. Porate, S. G. Kadwane and M. A. Waghmare, "Zero direct-axis current (ZDC) control for variable speed wind energy conversion system using PMSG," Energy Procedia, vol. 117, pp. 943–950, June 2017.

[21] S. M. Tripathi, A. N. Tiwari and D. Singh, "Optimum design of proportional-integral controllers in grid-integrated PMSG-based wind energy conversion system," International Transactions on Electrical Energy Systems,

vol. 26, No. 5, pp. 1006–1031, 2016.

[22] A. H. K. Alaboudy, A. A. Daoud, S. S. Desouky and A. A. Salem, "Converter controls and flicker study of PMSG-based grid connected wind turbines," Ain Shams Engineering Journal, vol. 4, No. 1, pp. 75–91, March 2013.

[23] A.-R. Youssef, M. A. Sayed, M. Abdel-Wahab and G. S. Salman, "MPPT control technique for direct-drive five-phase PMSG wind turbines with wind speed estimation," International Journal of Sustainable and Green Energy, vol. 4, No.5, pp. 195-205, September 2015.

[24] K. Milev, V. Yaramasu, A. Dekka and S. Kouro, "Modulated Predictive Current Control of PMSG-Based Wind Energy Systems," in 2020 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), Tehran, pp. 1–6, 4-6 February 2020.

[25] M. Abdelrahem, C. Hackl, Z. Zhang and R. Kennel, "Sensorless control of permanent magnet synchronous generators in variable-speed wind turbine systems," Proceedings of Power and Energy Student Summit (PESS 2016), 2016..

[26] M. Abdelrahem, C. M. Hackl and R. Kennel, "Implementation and experimental investigation of a sensorless field-oriented control scheme for permanent-magnet synchronous generators," Electrical Engineering, vol. 100, No. 2, pp. 849–856, June 2018.

[27] M. Fawzi, A. E. Kalas, M. H. Elfar and O. Elbakssawy, "A study on energy balancing and control of modular multi-level converters," in 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), Cario, pp. 164–170, 27-29 December 2016.

[28] S. Li, T. A. Haskew and L. Xu, "Conventional and novel control designs for direct driven PMSG wind turbines," Electric Power Systems Research, vol. 80, No. 3, pp. 328–338, March 2010.

[29] H. H. H. Mousa, A.-R. Youssef and E. E. M. Mohamed, "Model predictive speed control of five-phase permanent magnet synchronous generator-based wind generation system via wind-speed estimation," International Transactions on Electrical Energy Systems, vol. 29, No. 5, p. e2826, May 2019.

[30] V. Yaramasu and B. Wu, Model predictive control of wind energy conversion systems. John Wiley & Sons, 2016.

[31] J. Rodriguez et al., "Predictive current control of a voltage source inverter," IEEE transactions on industrial electronics, vol. 54, No. 1, pp. 495–503, February 2007.

[32] H. A. Young, M. A. Perez, J. Rodriguez and H. Abu-Rub, "Assessing finite-control-set model predictive control: A comparison with a linear current controller in two-level voltage source inverters," IEEE Industrial Electronics Magazine, vol. 8, No. 1, pp. 44–52, March 2014.

[33] J. Rodriguez and P. Cortes, Predictive control of power converters and electrical drives, vol. 40. John Wiley & Sons, 2012.

[34] P. Cortés, M. P. Kazmierkowski, R. M. Kennel, D. E. Quevedo and J. Rodriguez, "Predictive control in power electronics and drives," IEEE Transactions on industrial electronics, vol. 55, No. 12, pp. 4312–4324, Dec. 2008.

[35] J. Rodriguez et al., "State of the art of finite control set model predictive control in power electronics," IEEE Transactions on Industrial Informatics, vol. 9, No. 2, pp. 1003–1016, October 2012.

[36] S. Kouro, P. Cortés, R. Vargas, U. Ammann and J. Rodriguez, "Model predictive control—A simple and powerful method to control power converters," IEEE Transactions on industrial electronics, vol. 56, No. 6, pp. 1826–1838, November 2008.

[37] S. Vazquez, J. Rodriguez, M. Rivera, L. G. Franquelo and M. Norambuena, "Model predictive control for power converters and drives: Advances and trends," IEEE Transactions on Industrial Electronics, vol. 64, No. 2, pp. 935–947, November 2016.

[38] A.-R. Youssef, E. E. M. Mohamed and A. I. M. Ali, "Model predictive control for grid-tie wind-energy conversion system based PMSG," in 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), Aswan, pp. 467–472, Feb. 2018.

[39] E. G. Shehata, "A comparative study of current control schemes for a direct-driven PMSG wind energy generation system," Electric Power Systems Research, vol. 143, pp. 197–205, February 2017.

[40] E. J. Fuentes, C. Silva, D. E. Quevedo and E. I. Silva, "Predictive speed control of a synchronous permanent magnet motor," in 2009 IEEE International Conference on Industrial Technology, Churchill, pp. 1–6, Feb. 2009.

[41] E. J. Fuentes, C. A. Silva and J. I. Yuz, "Predictive speed control of a two-mass system driven by a permanent magnet synchronous motor," IEEE Transactions on Industrial Electronics, vol. 59, No. 7, pp. 2840–2848, June 2011.

[42] M. Preindl and S. Bolognani, "Model predictive direct speed control with finite control set of PMSM drive systems," IEEE Transactions on Power Electronics, vol. 28, No. 2, pp. 1007–1015, Feb. 2012.

[43] J. Gao and J. Liu, "A Novel FCS Model Predictive Speed Control Strategy for IPMSM Drives in Electric Vehicles," in IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, vol. 1, pp. 3169–3173, 14-17 October 2019.

[44] A. Formentini, A. Trentin, M. Marchesoni, P. Zanchetta and P. Wheeler, "Speed finite control set model predictive control of a PMSM fed by matrix converter," IEEE Transactions on Industrial Electronics, vol. 62, No. 11, pp. 6786–6796, June 2015.

[45] M. Abdelrahem, C. Hackl, R. Kennel and J. Rodriguez, "Sensorless predictive speed control of permanent-magnet synchronous generators in wind turbine applications," in PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, pp. 1–8, 7-9 May 2019.

[46] F. Ertürk, "Investigation of modular multilevel converter control methods," Master's Thesis, MIDDLE EAST TECHNICAL UNIVERSITY, Turkey, 2015.

[47] B. Wu, Y. Lang, N. Zargari and S. Kouro, Power conversion and control of wind energy systems, vol. 76. John Wiley & Sons, 2011.

[48] M. Allouche, S. Abderrahim, H. Ben Zina and M. Chaabane, "A Novel fuzzy Control Strategy for Maximum Power Point Tracking of Wind Energy Conversion System," International Journal of Smart Grid-ijSmartGrid, vol. 3, No. 3, pp. 120–127, September 2019.

[49] A. Belkaid, K. Kayisli and R. Bayindir, "Modeling of a Permanent Magnet Synchronous Generator in a Power Wind Generation System with an Electrochemical Energy Storage," International Journal of Smart Grid-ijSmartGrid, vol. 2, No. 4, pp. 197–202, December 2018.

[50] S. Kouro, M. A. Perez, J. Rodriguez, A. M. Llor and H. A. Young, "Model predictive control: MPC's role in the evolution of power electronics," IEEE Industrial Electronics Magazine, vol. 9, No. 4, pp. 8–21, Dec. 2015.

[51] R. N. Fard, "Finite control set model predictive control in power converters," Master's Thesis, Norwegian University of Science and Technology, Norway, 2013.

[52] M. Abdelrahem, C. M. Hackl and R. Kennel, "Simplified model predictive current control without mechanical sensors for variable-speed wind energy conversion systems," Electrical Engineering, vol. 99, No. 1, pp. 367–377, March 2017.