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Integral Sliding Mode Controller for Grid-Tie Wind-Energy Conversion System Based PMSG

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Abstract: *This paper suggests an Integral Sliding Mode Control (ISMC) strategy for enhancing the maximum power form wind energy conversion system (WECS) based on 1.5 MW PMSG. The ISMC is applied for optimal operation of a PMSG wind turbine (WT). The PMSG is tied to the utility grid through a three-phase back-to-back (BTB) converter. The maximum power available from the WECS is harvested by applying the control algorithm to the machine side converter (MSC). The MSC depend on the ISMC to track the rotor speed to reference value. Moreover, the dc-link voltage regulation is achieved using the grid-side converter (GSC). A model of directly driven PMSG based variable-speed WECS is developed and imitated using MATLAB/SIMULINK environment. The ISMC gives a good dynamic performance under wide wind speed variation. The effectiveness of the proposed control approach is validated through extensive simulation results.*

Index Terms*: Wind energy, PMSG, SMC,ISMC, MPPT.*

I. INTRODUCTION

The increased global consumption of electricity, global warming and environmental impact problems, and continues search for fossil fuels alternatives are the main motivates to use renewable energy sources (RESs). Wind energy is considered one of the most important RESs owing to its environmental and commercial merits[1].

Several types of the wind turbines are the fixed speed wind turbine (FSWT) and the variable speed wind turbine (VSWT) .The fixed speed wind turbine (FSWT) has simple construction and narrow wind speed range compared to the variable speed wind turbine (VSWT).The VSWT has several merits such as high captured wind energy. Several generator types are employed in variable-speed WECSs such as; the squirrel cage induction generator (SCIG) [2], the Doubly Fed Induction Generator (DFIG) [3,4] and the permanent magnet synchronous generators (PMSG) [5,6].The Doubly Fed Induction Generator (DFIG) based on VSWT have been the dominant technology in the market.Although DFIGs has wide commercial applications, researchers are more attractive for utilizing PMSGs in variable-speed WECSs. The several merits of PMSGs contribute to enhancing WECSs efficiency.The PMSG are used other configurations of VSWT are used withlarger capacity, lower cost, and higher reliability.The wind energy conversion system (WECS) consists of a PMSG which is directly connected to the wind turbine (WT). The three-phase statorterminals of the PMSG are linked to the utility grid (UG)through a back-to-back (BTB)through the DC-link capacitor. The machine side converter (MSC) maximizes the generated power while the grid side converter (GSC) integrates the active power intothe UG with unity power factor (UPF)[7].

To extract the maximum power from the WECS at any time, several types of the maximum power point tracking (MPPT) are considered. MPPT strategies are categorized to the tip-speed ratio (TSR) [8], wind speed estimation (WSE) [9]and perturbation and observation method (PO) [10]. In TSR-MPPT strategy based on the wind speed measurement to find theoptimal rotor speed. The TSR is a simple and fast algorithm to track the rotor speed to its optimal value. However, the TSR is based on the system parameters. The wind speed estimation (WSE) techniques require an exact estimation of wind velocity, which determines the tracking accuracy and the captured energy from the wind energy conversion system. Moreover, the wind speed measurement offers transient and load reduction independent on the accuracy of estimation techniques. In addition, inaccurate WSE algorithm leads to the operating in pitch control region below the rated wind speed. This drawback causes for operating the pitch control in order to reduce the mechanical stress on wind turbine is driven train, the pitch control turns wind turbine blades faraway facing the wind which causes a reduction on the power coefficient and increases the pitch angle above zero. These drawbacks reduce the captured wind power and overall performance.

Several types of controlmethods have been used to regulate the rotor speed for extract the maximum power with high efficiency and high response [11].Classical PI controllers are used due to their simple constructionand design. However,the PI controller have many drawbacks such as; difficult parameters tuning,poor dynamic response with overshoot [12].For good performance and fast dynamic response, the Sliding Mode Control (SMC) is one of the most effective nonlinearcontrollers with uncertainties [13]. In order to overcome thesteady state error problem and improve the sliding surface, IntegralSliding Mode Control (ISMC) is designed using an integral slidingsurface [14,15].

In this paper, an ISMC strategy for 1.5 MW PMSG WECS is proposed.The PMSG is tied to the utility gridat the point of common coupling (PCC) via a three-phase back-to-back (BTB) converter. Two control schemes are developed for machine- and network-side converters. A shunt capacitor is employed as a dc-link between the two converters.The ISMC is applied to regulate the rotor speed at optimal value under wind speed variations.

This article is prepared as follows; section II presents the WECS system modeling. The MPPT technique applied in this work is discussed in section III. Section IV discuss the control of the MSC and GSC. The principles of ISMC is discussed in section V. The system results are depicted and analyzed in section VI. Finally, section VII gives conclusions of the work.

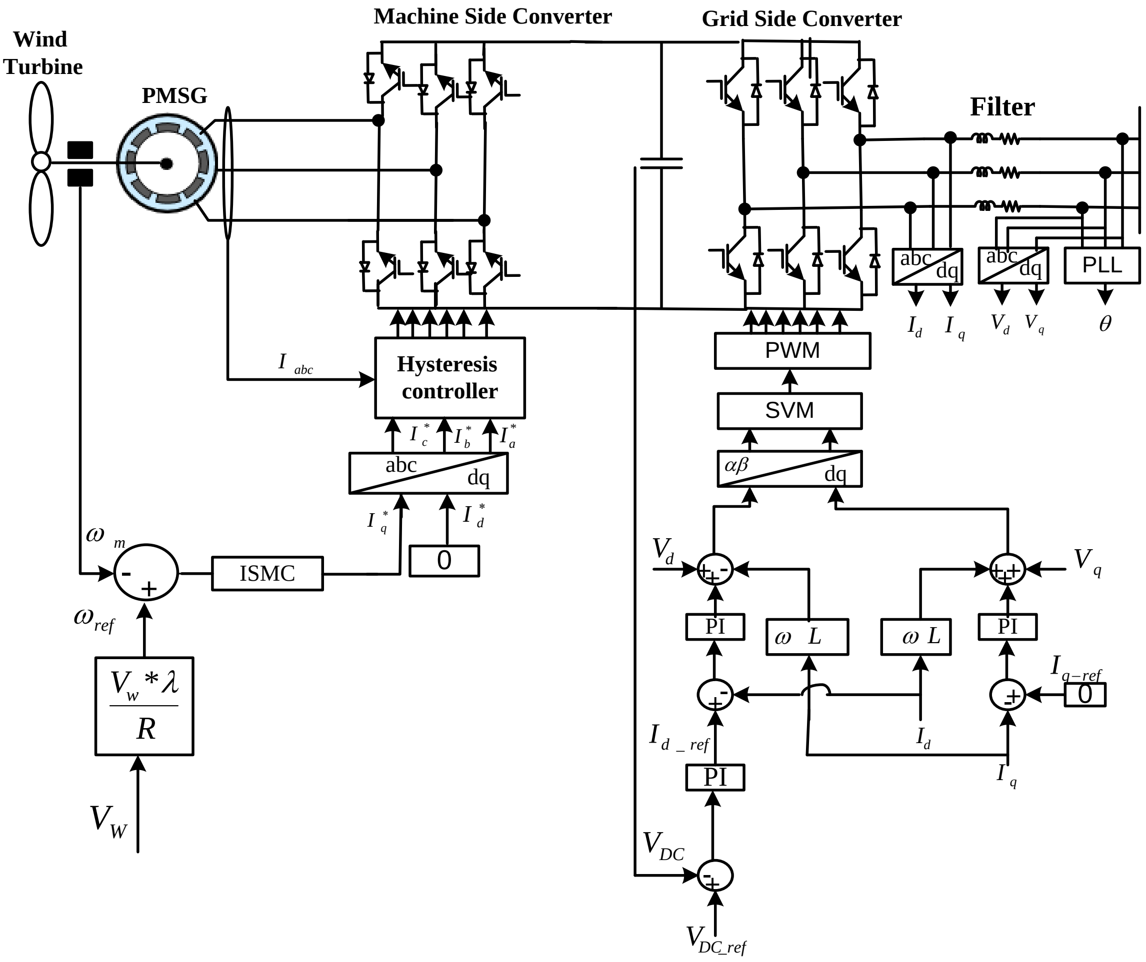


Fig. 1. Wind Energy Conversion System configuration.

II. WIND ENERGY CONVERSION SYSTEM

Fig.1 shows the configuration of the WECS based on 1.5 MW PMSG. The PMSG linked to utility grid through the BTB converter through the DC-link capacitor. The machine side converter (MSC) maximizes the generated power while the grid side converter (GSC) integrates the active power into the UG with unity power factor (UPF). The ISMC is applied to maintain the rotor speed at optimal value with fast response.

A. Wind Turbine Model.

For a variable speed WT, the mechanical power and mechanical torque are given as follows [15] :

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

$$T_m = \frac{P_m}{\omega_m} = \frac{1}{2}\frac{\rho A C_{p(\lambda,\beta)}V_w^3}{\omega_m} \qquad (2)$$

where P_m is the mechanicalpower, T_m is the mechanical torque of wind turbine, C_p is the turbine power coefficient ρ is the air density , A is the area swept by the turbine blades , V_w is the wind speed and ω_m is the mechanical rotor speed .

The tip speed ratio $\lambda$and the turbine power coefficientsC_p are presented as follows:

$$\lambda = \frac{\omega_m R}{V_w} \qquad (3)$$

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \qquad (4)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \qquad (5)$$

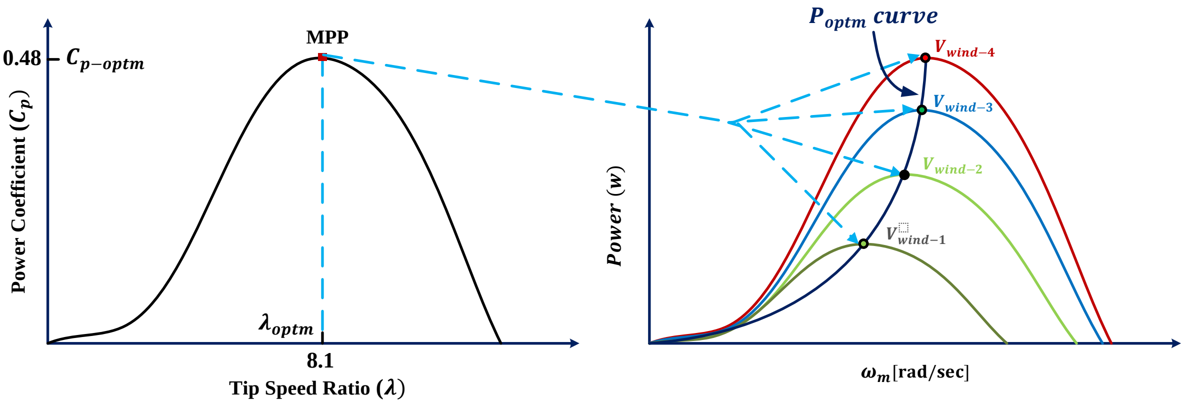


Fig.2 Power characteristic curve

where R is the radius of the turbine blade, β is pitch angle and $C_1 - C_{6,}$ are the turbine coefficient. In this study, assuming fixed rotorpitch, the pitch angle β is set to zero. However, a

MPPT algorithm is permissible only for variable speed WTs and the approximated coefficient values are given as: $C_1 = 0.5167$,$C_2 = 116$,$C_3 = 0.4$,$C_4 = 5$, $C_5 = 21$, and$C_6 = 0.0068$.

Fig.2 shows the relation between C_p and λ when β equals zero degree. Moreover, the power-speed characteristic is illustrated in Fig.2. To extract the maximum power the wind turbine operate at optimum values C_p is 0.48 and $\lambda$is 8.1.

B. Permanent Magnet Synchronous Generator Model

The voltage equations of a three-phase PMSG expressed in the rotor reference frame using an extended Park transformation as follows[6]:

$$V_d = R_s i_d + L_d\frac{di_d}{dt} - L_q\omega_e i_q \qquad (6)$$

$$V_q = R_s i_q + L_q\frac{di_q}{dt} + L_d\omega_e i_d + \psi\omega_e \qquad (7)$$

where $V_d$and V_q represent the stator voltages in the (d,q) axis, $i_d$and i_q represent the currents in the (d,q) axis, R_s represents stator resistance, L_d, L_q represent the (d,q) axis inductances, $\omega_e = p\omega_m$ (p is number of pole pairs,ω_m represents the turbine rotor angular speed) and ψ is the permanent flux linkage.

The developed torque of the PMSG can be expressed as:

$$T_e = \frac{3}{2} p\psi i_q \qquad (8)$$

The mechanical equation of the PMSG is given by:

$$T_m = T_e + f\omega_m + J\frac{d\omega_m}{dt} \qquad (9)$$

where f is the friction coefficient, $J$is the total moment of inertia,T_m is the mechanical torque produced by a WTandT_e is electromagnetic torque of PMSG.

III. MAXIMUM POWER POINT TRACKING TECHNIQUES

Several MPPT techniques are used to maintain the mechanical power to its maximum value for all wind speed conditions. Among these techniques the tip speed ratio TSR technique adjusts the rotor speed to its optimum values at different wind speeds, however the TSR technique is based on measuring the wind and rotor speeds. Also, the reference rotor speed at different wind speedsis calculated as follows:

$$\omega_{ref} = \frac{\lambda_{opt} * R}{V_w} \qquad (10)$$

whereω_{ref} is the reference rotor speed, λ_{opt} is the optimum TSR, R is the blade radius and V_w is the wind speed. It is obvious that the TSR control is a simple MPPT strategy but extremely reliant on the accuracy of the wind speed measurement using an anemometer which adds to the system cost [8].

From Eq.(9) the control of generator speed can be achieved by the control of electromagnetic torque. Moreover, from Eq.(8) the electromagnetic torque is proportional to the q-axis current of PMSG, hencethe rotor speed can be controlled by changing the q-axis current of PMSG.

$$\mathrm{i}_{qref} = \frac{2}{3 * \mathrm{P} * \Psi} * T_{em} \qquad (11)$$

IV. CONTROL OF MACHINE SIDE AND GRID SIDE CONVERTERS.

The MSC is used to regulatethe rotor speed to its optimal values at different wind speeds. Moreover, the WT operates at maximum power under wind speed variations. The MSC is used to adjust the rotor speed through a ISMCto its optimal value. On the other hand, the GSC is used to regulate thedc-link capacitor voltage to its reference value. Furthermore, the GSC is used to adjust the dq-axis grid current to its reference value.

V. INTEGRAL SLIDING MODE CONTROL IMSC

In the machine side converter MSC, the ISMC controller is applied to maintain the rotor speed at optimal value. The proposed ISMC control strategy is applied to reducelimitations of the PI controller. The mathematical model equations to improve the sliding surface and reduce the steady state error are demonstrated in [16]. The proposed ISMC reduce many problems compared to traditional SMC such as; overcomes the chattering problem and solves the reaching phase instability problem. The main objective of the ISMC enhance the maximum power by tracking the optimal rotor speed according to wind speed variations. In general, the designing of the proposed ISMC has two steps. First, is to develop the sliding surface and second, is to obtain the controller effort function (U) [14].

The sliding surface function is formulated as:

$$S_\omega = K_p e_\omega + K_i \int e_\omega \, dt \qquad (18)$$

where the speed error is $e_\omega = \omega_{ref} - \omega_m$,K_p and K_i are the positive gains.

By taking the time derivative of S_ω and e_ω ,

$$\dot{e_\omega} = \dot{\omega_{ref}} - \dot{\omega_m} \qquad (19)$$

$$\dot{s_\omega} = K_p \, \dot{e_\omega} + K_i \, e_\omega \qquad (20)$$

hence,

$$\dot{s_\omega} = K_p \, (\dot{\omega_{ref}} - \dot{\omega_m}) + K_i \, e_\omega \qquad (21)$$

using (13) and substituting with $\dot{\omega_m}$ into (21),

$$\dot{s_\omega} = K_p \, (\dot{\omega_{ref}} - \frac{1}{J}(T_m - \frac{5}{2} \, p\psi \, i_{q1} - f \, \omega_m)) + K_i \, e_\omega \qquad (22)$$

arranging (22),

$$\dot{S}_{\omega} = \underbrace{K_p \ \dot{\omega}_{ref} + K_i \ e_{\omega}}_{C} - \underbrace{\frac{K_p}{J}(T_m - f \ \omega_m)}_{m} + \underbrace{\frac{2.5 \ K_p}{J} \ p\psi}_{D} \ \underbrace{i_{q1}}_{U} \tag{23}$$

$$\dot{S}_{\omega} = C - M + D \ U \tag{24}$$

using system uncertainties,

$$\dot{S}_{\omega} = C - (M + \Delta M) + (D + \Delta D) \ U \tag{25}$$

then, the lumped uncertainties can be represented as:

$$W = -(M + \Delta M) + \Delta D U \tag{26}$$

$$\dot{S}_{\omega} = C + DU + W \tag{27}$$

the sliding surfaces can be expressed as:

$$\dot{S}_{\omega} = S_{\omega} = 0 \tag{28}$$

so that the ISMC control effort can be formulated as:

$$U^{*} = D^{-1} \left(- C - \rho_{\omega} \ sat(S_{\omega}) \right) \tag{29}$$

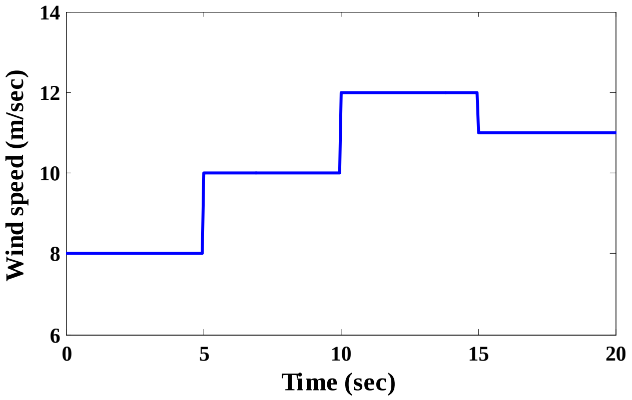
as a replacement of the sign function, the sat function is used to minimize the chattering problem, also adding two terms for solving the reaching phase instability problem. The K_c and K_t are selected to attain the optimum performance and minimize the dynamic system disturbance.

VI. SIMULATION RESULTS AND DISCUSSION.

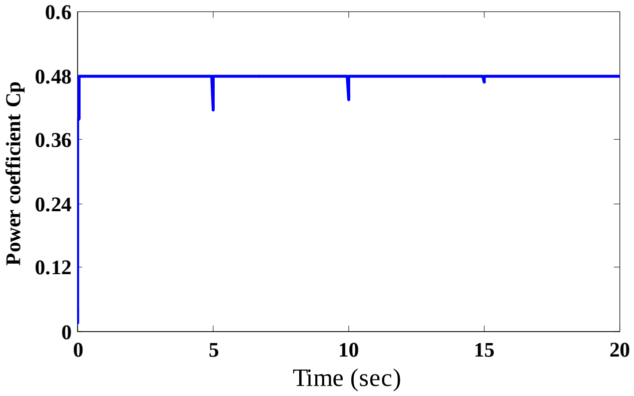
To show the validity and effectiveness of the system, simulation results have been carried out by Matlab/Simulink software. The parameters of the system under study are given in the Appendix.

To study the characteristics of the TSR algorithm in tracking the MPP under different variation in the wind speed. It is assumed that the wind speed profile varies up and down as a step function with mean wind speed of 10 m/sec.Fig.5 represents the actual wind speed, the measured and reference generator speed, the actual and maximum mechanical power, the turbine's power coefficient, the turbine tip speed ratio and the torque of the PMSG. It is obvious that the controller gives a good tracking of the actual and reference values of the rotor speed. The difference in power between the determined electrical and mechanical powers isvery small. On the other hand, it can be observed that the system operates at the optimal power coefficient value (0.48). Moreover, the tip speed ratio reaches maximum value (8.1). Also, the turbine torque T_m and generator torque T_e are coincide well.

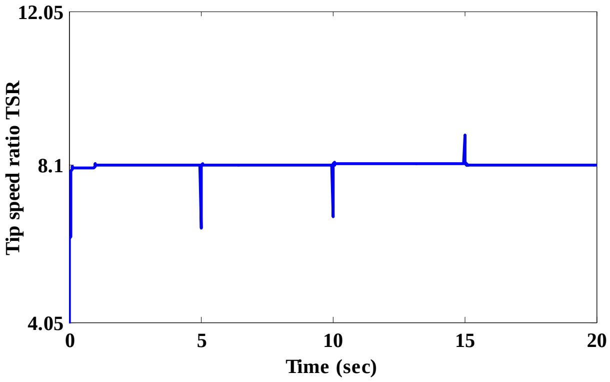
The grid-side converter controller isexaminedunder step-changing wind speed profile. Fig.6 shows the dc-link voltage, the grid voltage and current, the grid power and the power factor. The controller regulates the actual value of dc-link voltage to the reference level. On the other hand, to achieve unity power factor, the grid voltage and current are kept in-phase. The injected active power has a step change according to the change in the wind speed, whereas the reactive power is zero to achieve unity power factor.



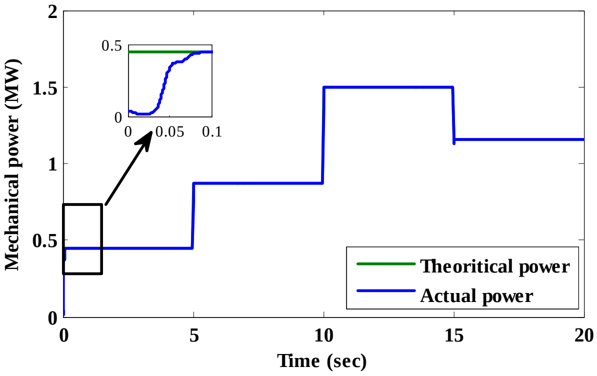
(a) Step-wind speed



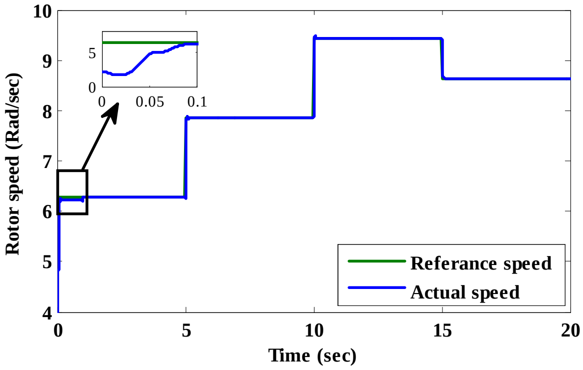
(b) Power coefficient



(c) Tip speed ratio TSR

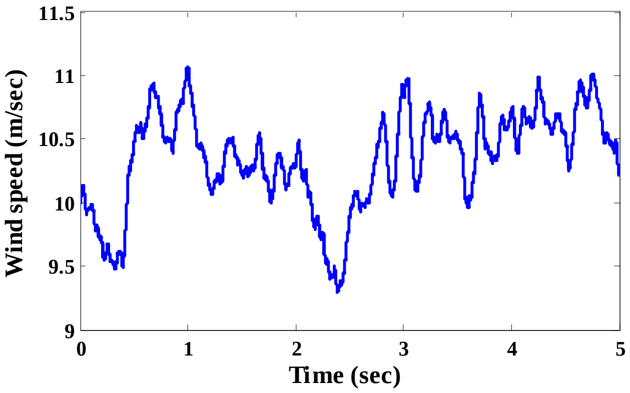


(d) Mechanical power

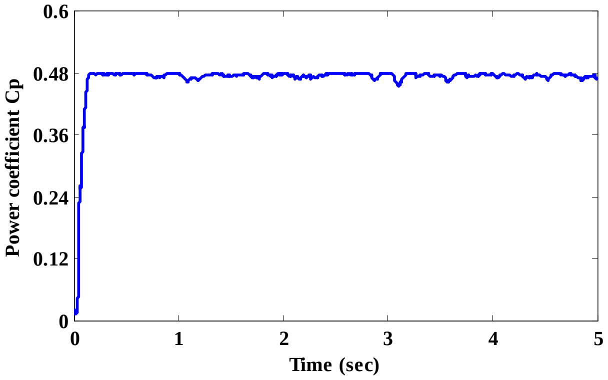


(e) Rotor speed

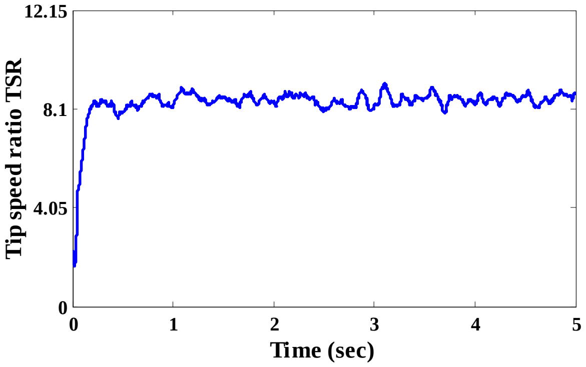
Fig. simulation results under step- wind speed



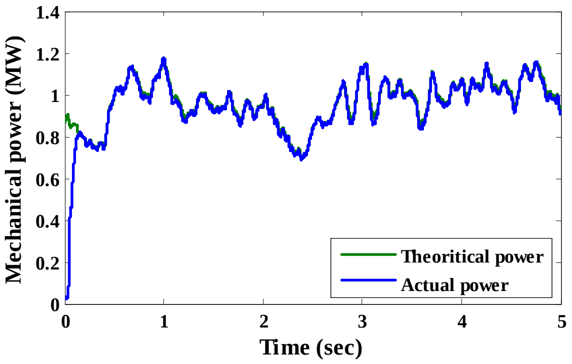
(a) Random-wind speed



(b) Power coefficient



(c) Tip speed ratio TSR



(d) Mechanical power
Fig. simulation results under random-wind speed

VII. CONCLUSIONS.

This article suggests the ISMC strategy to improve the performance of the MSC at dynamic response. The ISMC is applied to regulate the rotor speed to its optimal value with fast response and small overshoot under wind speed variations. The electromagnetic torque control is realized through ISMC where the q-axis current is used to control the rotational speed of the generator according to the variation of wind speed. Also, the ISMC has been proven as a good power controller in grid side. Computer simulations have been carried out in order to evaluate the effectiveness of the ISMC. The results proved that the ISMC has accurate tracking performance at different wind speed.

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APPENDIX

SYSTEM PARAMETERS [6]

Specification of wind turbine

Blade radius	$R = 1.8\text{m}$
Air density	$\rho = 1.225\ \text{kg/m}^3$
Optimal tip speed ratio	$\lambda_{opti} = 8.1$
Maximumpower coefficient	$C_{p-max} = 0.48$

Three-phase PMSG parameters

Pole pairs number	$n_p = 5$
Stator resistance	$R_s = 0.425\ \Omega$
Direct-axis inductance	$L_d = 0.00835\ \text{H}$
Quadrature-axis inductance	$L_q = 0.00835\ \text{H}$
Moment of inertia	$J = 0.01197\ \text{kg. m}^2$
Flux linkage	$\psi = 0.433\ \text{Wb}$

DC bus and gird parameters

dc-link voltage	$V_{dc} = 750\ \text{V}$
Capacitor of the dc-link	$C = 2000\ \mu\text{F}$
Grid frequency	$F = 50\ \text{Hz}$
Grid resistance	$R_g = 0.015\ \Omega$
Grid inductance	$L_g = 0.002\ \text{H}$

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