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A novel optimum tip speed ratio control of low speed wind turbine generator based on type-2 fuzzy system

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ABSTRACT

Variable speed control of wind turbine generator systems have been developed to get maximum output power at every wind speed variation, also called Maximum Power Points Tracking (MPPT). Generally, MPPT control system consists of MPPT algorithm to track the controller reference and generator speed controller. In this paper, MPPT control system is proposed for low speed wind turbine generator systems (WTGs) with MPPT algorithms based on optimum tip speed ratio (TSR) and generator speed controller based on field oriented control using type-2 fuzzy system (T2FS). The WTGs are designed using horizontal axis wind turbines to drive permanent magnet synchronous generators (PMSG). The simulation show that the MPPT system based optimum TSR has been able to control the generator output power around the maximum point at all wind speeds.

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1. INTRODUCTION

Indonesia's geographical conditions located in the tropics only have low wind speeds. Therefore, wind power plants that are suitable to be developed are low speed wind turbine generator systems (WTGs). Several types of generators have been used, such as Permanent magnet synchronous generator (PMSG) [1-2] and induction generator [3-6]. PMSG is widely used for low speed WTGs, because it has high efficiency, high power density with compact size and can be applied directly without a gearbox [1-2, 7]. In this paper proposed low speed WTGs using PMSG driven by horizontal axis wind turbine in stand alone configuration.

To improve the WTGs efficiency, the Maximum Power Point Tracking (MPPT) is proposed to obtain maximum output power. Generally, MPPT systems consists of the MPPT algorithm and the speed controllers. Several MPPT algorithms have been developed, such as optimum torque, optimum TSR, perturbation and observation and MPPT based on artificial intelligence [8-16]. MPPT based on the optimum TSR is proposed, because more accurate than other algorithms. PMSG speed control widely developed with vector control methods, such as direct torque control and field oriented control. The field oriented control method provides a smoother speed response than the direct torque control method [17], so this method is chosen. In the field oriented control method, generator speed is controlled by regulating the dq-axis stator current. In this paper, field oriented control based on a constant torque angle method is used. Several methods have been applied to adjust the stator current, such as PI controller [10], sliding mode control [13], fuzzy logic control [6] and adaptive robust control [18]. In this paper, the stator current is regulated using type-2 fuzzy system (T2FS) method. The mayor difference T2FS with type-1 fuzzy system are the memberships function T2FS are presented by upper membership function and lower membership function. This makes T2FS more accurate than type-1 fuzzy system to handle the uncertainty of parameters [19-21].

T2FS usage is expected to increase the reliability of the system to control the generator speed at maximum power point.

2. THE PROPOSED WIND TURBINE GENERATOR SYSTEM

The proposed stand alone wind turbine generator system (WTGs) is shown in Figure 1. The WTGs consists of horizontal axis wind turbine, PMSG, voltage source converter, dc voltage supply for PMSG speed control in the initial conditions, resistor load and MPPT system that consists of a MPPT algorithm based on optimum TSR and the speed control based on field oriented control. In this method, the generator speed is regulated by adjust the q-axis stator current using T2FS, while the d-axis stator current is kept constant zero. Furthermore, the reference of dq-axis stator currents are compared to the measured stator current and its error is used as input of the hysteresis current regulator pulse width modulation (HCC-PWM) to modulate the voltage source converter switches. With this concept, the voltage source converter will control the dq-axis stator current according to the reference current obtained from T2FS, so that it will indirectly regulate PMSG speed according to the reference speed at the maximum power.

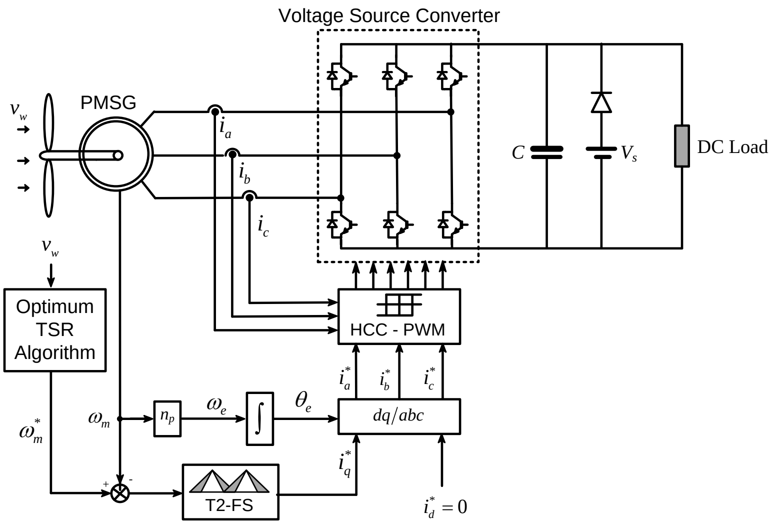


Figure 1. The proposed stand alone WTGs

2.1. Horizontal axis wind turbine

Horizontal axis wind turbine (HAWT) is used to drive the generator based on the mechanical power it captures from wind speed. The mechanical power of a wind turbine (P_m) is determined by wind speed (v_w), air density (ρ), blade radius of wind turbine (R) and wind turbine power coefficient (C_p), which is written:

$$P_m = 0.5\, C_p(\lambda,\beta)\, \rho\, \pi\, R^2\, v_w^3 \tag{1}$$

Power coefficient (C_p) is the ratio between the mechanical power produced by a wind turbine (P_m) and the wind power captured by a wind turbine blade. The C_p value is determined by pitch angle of blade (β) and tip-speed ratio (λ) [13]. TSR is the ratio of wind turbine rotation speed to wind speed, which is written as:

$$\lambda = \frac{\omega_m R}{v_w} \tag{2}$$

2.2. Permanent magnet synchronous generator

The MPPT control system based on optimum TSR is applied by controlling the PMSG speed in vector control method. In vector control, PMSG is modeled in *dq*-axis form. The stator current of PMSG in *dq*-axis can be written as:

$$i_d = \int \left(\frac{v_d}{L_d} - \frac{R_s}{L_d} i_d + \omega_e \ i_q \right) dt \quad (3)$$

$$i_q = \int \left(\frac{v_q}{L_q} - \frac{R_s}{L_q} i_q - \omega_e \ i_d - \omega_e \frac{\psi_m}{L_q} \right) dt \quad (4)$$

where R_s, ψ_m, and ω_e are the stator resistance, permanent magnet flux and the electrical speed of PMSG, respectively. v_d,v_q and L_d, L_q are the stator voltages and the stator inductances, respectively. The mechanical dynamic of PMSG can be written as :

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e - B\omega_m}{J} \text{ with } T_e = \frac{3}{2} n_p \left(\psi_m \ i_q \right) \quad (5)$$

where J, B, ω_m and n_p are inertia moment, friction coefficient, mechanical speed and pole pair number of PMSG, respectively.

3. OPTIMUM TIP SPEED RATIO CONTROL

Optimum Tip-Speed Ratio (TSR) control is designed based on the mechanical characteristics of the wind turbine. The mechanical power of a wind turbine varies according to changes in wind speed and mechanical speed of the wind turbine. Mechanical power has one maximum point at each wind speed, which is at the maximum power coefficient point (C_{pmax}) and optimum TSR (λ_{opt}), as shown in Figure 2.

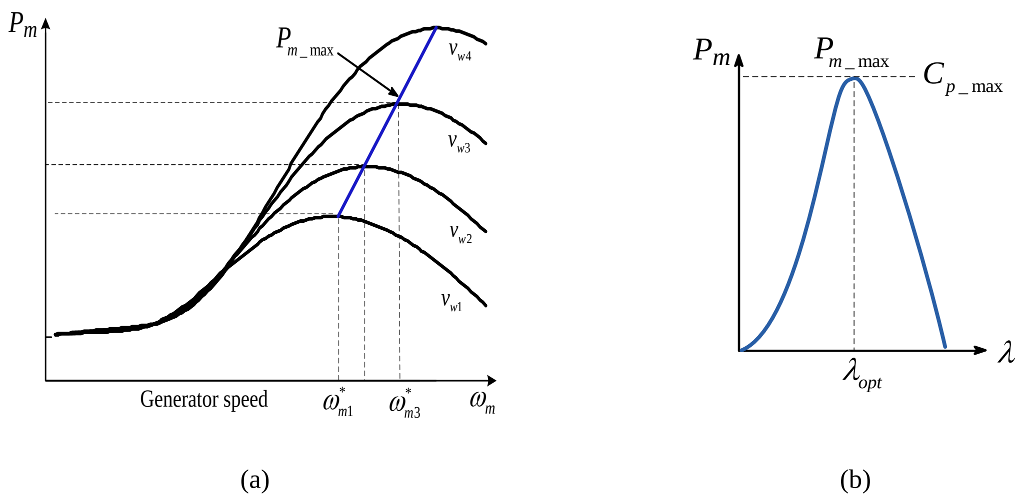


Figure 2. Wind turbine characteristics, (a) Mechanical power curve, (b) Power coefficient versus TSR

Optimum TSR control consists of MPPT algorithm to searching the reference speed at maximum power point and speed controller to regulate the generator speed according to the reference speed. The reference speed at the maximum power point can be calculated based on (2), which is written as:

$$\omega_m^* = \frac{\lambda_{opt} \ v_w}{R} \quad (6)$$

where λ_{opt} values in (2) are obtained through wind turbine testing. The generator speed controller is design using FOC method based on a constant torque angle. In this method, the generator speed is controlled by regulating the torque indirectly through controlling the q-axis stator using T2FS, while the d-axis stator current is kept constant zero. Figure 3 show the scheme of speed controller using T2FS.

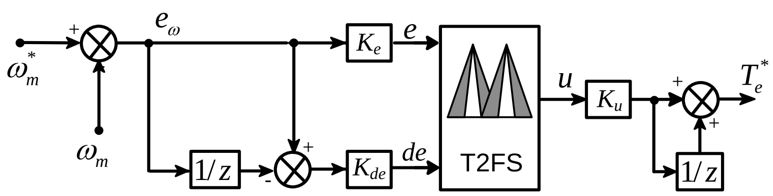


Figure 3. The scheme of speed controller using T2FS

T2FS is used to obtain the reference electromagnetic torque T_e^* with input speed errors *e* and speed error changes *de*. Afetr T_e^* is obtained from T2FS, then the reference dq-axis stator current can be written as :

$$i_q^* = \frac{2}{3}\frac{T_e^*}{\psi_m \; n_p} \text{ and } i_d^* = 0 \tag{7}$$

Stator current regulation is done by adjusting the modulation of converter switches based on HCC-PWM. PWM pulses are obtained using a hysteresis band with input the reference stator current from the speed controller and a measured stator current. This makes the stator current become controlled according to the reference current from the speed controller, therefore the generator operates at a speed corresponding to the reference speed at the maximum power point.

3.1. Type-2 fuzzy system

Type-2 Fuzzy System (T2FS) uses an interval membership function that has a Footprint of Uncertainty (FOU) which is limited by upper membership function (UMF) and lower membership function (LMF), thus the uncertainty of input parameters is easier to overcome [19-21]. T2FS structure consists of fuzzification, fuzzy inference, rule base and output processor which consists of type reduction and defuzzification. Fuzzification is the process of mapping real input data (crisp input) into a fuzzy set with linguistic variables. The T2FS input for speed control are the speed error *e* and the speed error changes *de*. If the input is expressed as *x*, then the crisp input membership function can be presented as:

$$\mu_X(x) = \left[\mu_e(x_e),\ \mu_{de}(x_{de})\right] \tag{8}$$

$$\mu_e(x_e) = \left[\underline{\mu}_e(x_e),\ \overline{\mu}_e(x_e)\right] \text{ and } \mu_{de}(x_{de}) = \left[\underline{\mu}_{de}(x_{de}), \overline{\mu}_e(x_{de})\right] \tag{9}$$

If crisp output is expressed as *y*, then the crisp output membership function can be presented with:

$$\mu_Y(y) = \mu_u(y_u) = \left[\underline{\mu}_u(y_u),\ \overline{\mu}_u(y_u)\right] \tag{10}$$

The membership function of crisp input and output are represented by triangular and trapezoidal membership functions with linguistic variables negative big (*NB*), negative medium (*NM*), negative small (*NS*), zero (*Z*), positive small (*PS*), positive medium (*PM*) and positive big (PB), as shown in Figure 4. Figure 4 shows that input *e* is presented with seven membership functions, input *de* has five membership and output functions *u* has seven membership functions. The T2FS rule is designed with the concept of diagonal rules. There are 35 rules used to determine T2FS output. T2FS rules are formulated by (11) and the T2FS rule base is detailed in Table 1:

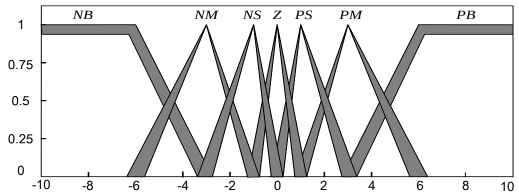
$$\text{R}^i = \text{if } e \text{ is } X_e^i \text{ and } de \text{ is } X_{de}^i \text{ then } U \text{ is } Y_u^i,\ i = 1,2,..,35 \tag{11}$$

where $X_e, Y_u \subseteq \left[NB, NM, NS, Z, PS, PM, PB\right]$ and $X_{de} \subseteq \left[NB, NS, Z, PS, B\right]$. Based on the rules in (11), T2FS inference with meet operations can be written as:

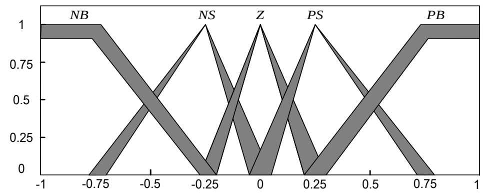
$$\mu_{R^i} = \mu_e(x_e^i) \prod \mu_{de}(x_{de}^i) \prod \mu_u(y_u^i) \tag{12}$$

with firing strength:

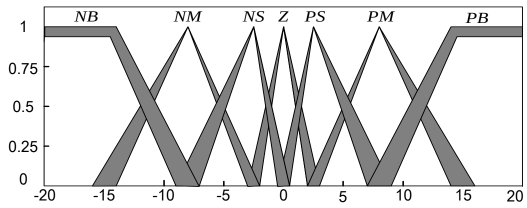
$$F^i(x^i)=\left[\left(\underline{\mu}_e^i(x_e^i)\times\underline{\mu}_{de}^i(x_{de}^i)\right),\left(\overline{\mu}_e^i(x_e^i)\times\overline{\mu}_{de}^i(x_{de}^i)\right)\right]\equiv\left[\underline{f}^i,\ \overline{f}^i\right] \tag{13}$$



(a)



(b)



(c)

Figure 4. Membership functions of T2FS, (a) input *e*, (b) input *de*, (c) output *u*

Table 1. Rule base of T2FS

d_e \ e	NB	NM	NS	Z	PS	PM	PB
PB	Z	PS	PS	PM	PM	PB	PB
PS	NS	NS	Z	PS	PS	PM	PM
Z	NM	NS	NS	Z	PS	PS	PM
NS	NM	NM	NS	NS	Z	PS	PS
NB	NB	NB	NM	NM	NS	NS	Z

After a fuzzy inference system, then type reduction is done using Center of Sets (COS), which is written as:

$$Y_{\cos}(x^i)=\bigcup_{\substack{f^i\in F^i(x^i)\\ y^i\in Y^i}}\frac{\sum_{i=1}^{n}f^iy^i}{\sum_{i=1}^{n}f^i}\equiv\left[y_l,y_r\right] \tag{14}$$

where Y_{COS} is a type-1 fuzzy interval, *yl* is the left point or the minimum value of *y* and *yr* is the right point or the maximum value of *y*, which can be calculated by the Karnik-Mendel algorithm, as discussed in [19]. After y_l and y_r are obtained, then the output of T2FS can be calculated by using:

$$y=u_i=\frac{y_l+y_r}{2} \tag{15}$$

The reference electromagnetic torque as the output of speed controller can be written as :

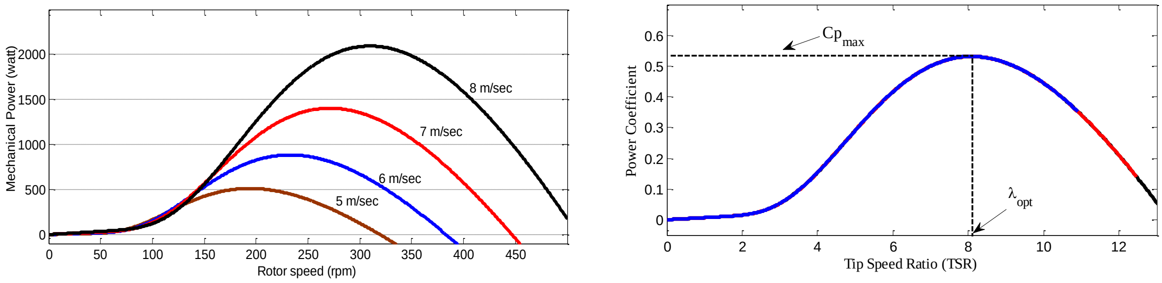
$$T_e^*=K_uu_i+u_{i-1} \tag{16}$$

Based on the reference electromagnetic torque in (16), the q-axis stator current can be calculated using (7). This arrangement of the q-axis stator current will adjust the rotor speed according to the reference speed for maximum outpout power of WTGs.

4. RESULTS AND ANALYSIS

The proposed optimum TSR control of WTGs based on T2FS is verified through simulation. The proposed system as shown in Figure 1 consists of horizontal axis wind turbine with blade radius 2 meter, PMSG with permanent magnet flux 0.175 Weber, pole pair numbers 18, momen of inertia 0.089 kg m^2 and friction coefficient 0.005 N.m.s/rad.

The first simulation was carried out to see the characteristics of wind turbines. at wind speeds that varied from 5 m/sec to 8 m/sec. Figure 5 shows the simulation results. The mechanical power of a wind turbine varies according to changes in wind speed and rotor speed, as shown in Figure 5(a). The mechanical power of a wind turbine has one maximum point at each wind speed. Figure 5(a) shows that the maximum power point has a different rotor speed at each wind speed. This maximum power point is at the point of maximum power coefficient and optimum TSR point. The simulation results show that this wind turbine has a maximum power coefficient of 0.5312 and an optimum TSR of 8.09, as shown in Figure 5(b). This value will be used as a reference to validate the proposed MPPT control system.



(a) (b)

Figure 5. Wind turbine characteristics, (a) Mechanical power, (b) power coefficient versus TSR

The next simulation was carried out to see the validity of the MPPT system with varying wind speeds, as shown in Figure 6(a). The MPPT control system based optimum TSR is carried out by controlling the generator speed at the maximum power point. Figure 6(b) shows the generator speed response. The design of the generator speed control system with T2FS-based FOC method has been able to control the generator speed according to the reference speed generated by the MPPT algorithm with a maximum error 9 rpm at transient conditions and ±2 rpm at steady state conditions, as shwon in Figure 6(c). This shows that the T2FS design has provided accurate results for controlling the electromagnetic torque through setting the q-axis stator current. This can be seen from the electromagnetic torque response in Figure 6(d). T2FS has successfully controlled the electromagnetic torque of generator to follow the mechanical torque of a wind turbine at its maximum power point, hence the generator speed also follows the reference speed at the maximum power point. This shows that the design of the optimum TSR-based MPPT algorithm has successfully tracked the reference speed at the maximum power point and speed control of the generator with the T2FS method has also succeeded in controlling the rotor speed of the generator according to the reference speed from the MPPT algorithm, so the maximum power of WTGs can be achieved at all wind speed variations.

The performances of MPPT control system for stand alone WTGs can be seen in Figure 7. The generator output power varies according to changes in wind speed, as shown by Figure 7(a). This generator output power variation is the maximum power point variation due to changes in wind speed. It is can be seen from the response of the wind turbine power coefficient and TSR as shown by Figure 7(b) and 7(c). In steady state, the TSR of wind turbine remain at the optimum point 8.09 even though the wind speed changes. The wind turbine power coefficient also remains at a maximum point 0.5312 although wind speeds vary. This shows that the MPPT control system design with T2FS-based optimum TSR method has successfully controlled the generator output power at maximum points at all wind speed variations. The simulation results in Figure 6 and Figure 7 also show that the MPPT algorithm based on optimum TSR can provide a smooth reference speed. This results in the generator speed response also being smooth, so that the generator voltage also has low ripples, as shown in Figure 7(d). The generator output voltage response on dc loads whose values vary according to changes in wind speed. The smooth response of the generator output voltage makes the generator output power also smooth, as shown in Figure 7(a).

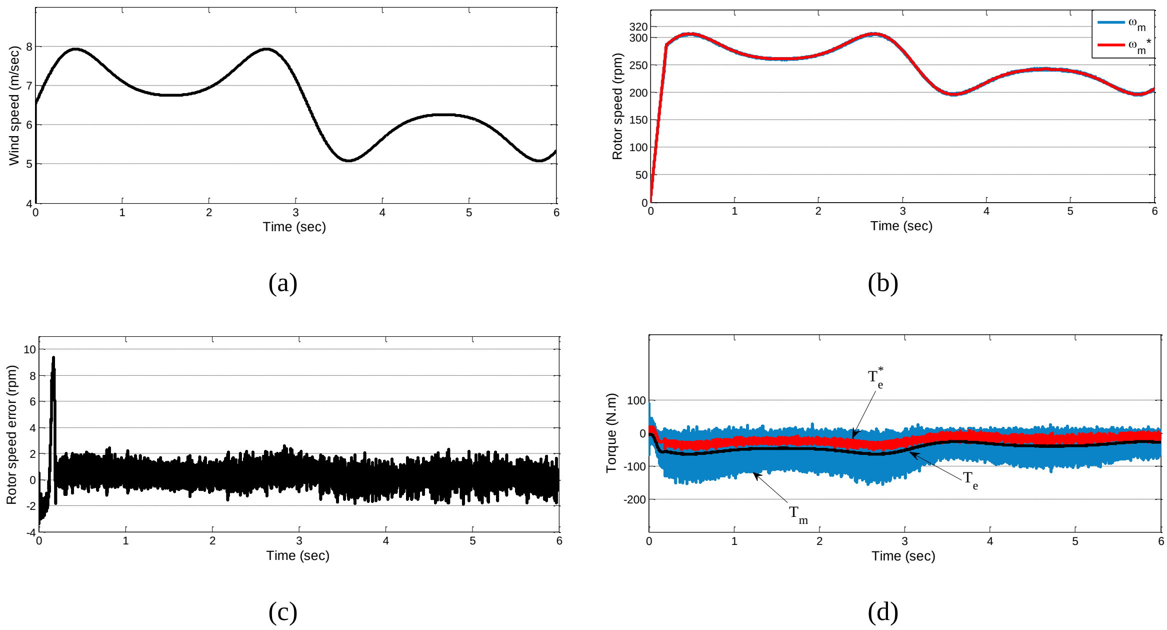


Figure 6. PMSG performances, (a) wind speed, (b) rotor speed, (c) rotor speed error, (d) torque

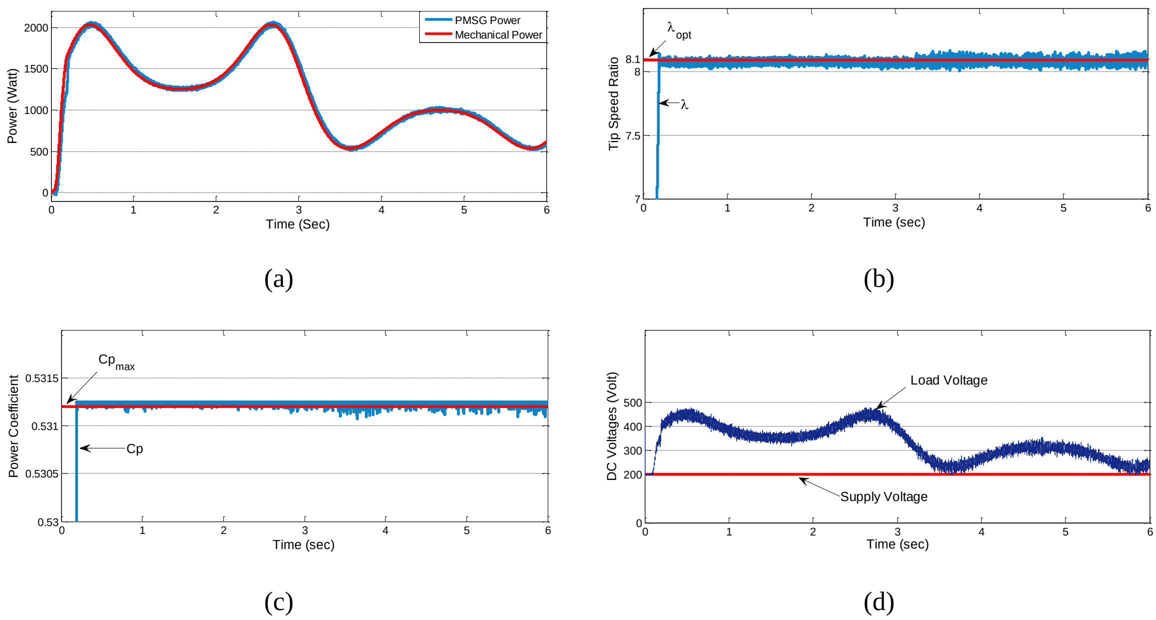


Figure 7. The MPPT performances, (a) power, (b) TSR, (c) power coefficient, (d) DC voltage

5. CONCLUSION

The proposed MPPT control system for direct driven WTGs based on optimum TSR using T2FS has successfully controlled the generator output power at maximum power points at all wind speed variations. This can be seen from the response of the wind turbine power coefficient that stays around the maximum point of 0.5312 and the TSR response which remains at the optimum point of 8.09 even though the wind speed varies. This shows that the design of MPPT algorithm based on optimum TSR for direct driven WTGs has successfully tracked the reference speed at the maximum power point and the T2FS design proposed to control electromagnetic torque has produced a generator speed that corresponds to the reference speed from the MPPT algorithm, so that the maximum output power of the generator can be obtained at all wind speed variations. The MPPT algorithm based on optimum TSR and the generator speed control based on T2FS based can provide a smooth generator speed, so the generator output power response also becomes smooth.

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