An Enhanced MPPT Fuzzy Control of a Wind Turbine Equipped with Permanent Magnet Synchronous Generator

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***Abstract*— In this paper a robust intelligent controller is adopted in order to fulfil maximum power point tracking (MPPT) algorithm for permanent magnet synchronous generator (PMSG) with the application of wind turbines. Conventional linear PI controller is simple and easy to implement but it has the drawback of dependence on system parameters especially in a wind energy conversion system with large amount of uncertainties as a sequence of wind speed variation. Due to inherent robustness to uncertainties in fuzzy logic controller, it can be used effectively in wind energy conversion system. However designing procedure and gain tuning could be a challenging approach. In this paper the initial parameters of FLC are obtained from the parameters of its well-tuned linear counterpart. This is a flexible control scheme that takes advantage of the best features of fuzzy control, robustness to uncertainties, and of PI controller, simple tuning procedure. This intelligent controller is designed in presence of mechanical parameters as well as mechanical torque disturbance, which is the most concerned uncertainty in wind turbines. Simulation results clearly shows performance of proposed robust fuzzy PI control system in maximum power points tracking in a wind energy conversion system.**

Keywords- fuzzy logic controller (FLC), maximum power point tracking (MPPT), permanent magnet synchronous generator (PMSG), field oriented control (FOC)

I. INTRODUCTION

Widely used energy sources, such as oil, natural gas, coal and nuclear, are finite and generate pollution. Clean renewable sources, such as solar, wave and wind have been vigorously developed over recent years and wind is now on the verge of being truly competitive with conventional sources.

Wind generation can be operated by constant speed and variable speed operation. A variable speed capability is costly to implement but its properties of increased energy capture, reduced noise emission and reduced fatigue loading throughout the structure mean that it is considered almost essential for most new designs.

There are mainly two kinds of generators, used in variable speed wind turbines: Doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). In comparison with DFIG, PMSG has several advantages such as the ability of operation over full range of generator speed, less weight, small in size, gearless drive, lowering maintenance expenses and improving low voltage ride through capability [1]. Based on these reasons the usage of PMSG based wind turbines are increasing widely in power systems.

Classical nonlinear controllers are mostly depending on model of system but we face some dynamics that isn't modeled in wind turbine applications and this can increase complexity, whereas fuzzy control isn’t so depend on model of system. Fuzzy logic controllers (FLCs) have a large success due to their advantages over classical approaches. Indeed, the authors in [2] presented a comparative study between three controllers of buck converters in which the simulation results showed the efficiency and robustness of fuzzy logic control compared to a classical PI (proportional integral) and sliding mode controllers. Although fuzzy control shows a good performance, there is still no mature methodology for designing and tuning the scaling gains [3]. Several approaches could be useful for designing the nominal scaling gains. One of them is the comparative design by using the well-tuned parameters of classical PID controller.

In this study, a fuzzy controller is proposed for maximum power point tracking of wind turbine equipped with PMSG which we are using comparative design for designing fuzzy controller. In this method, we obtain the initial parameters of FLC from the parameters of its well-tuned linear counterpart because the well-tuned linear counterpart is often available or could be easier to obtain.

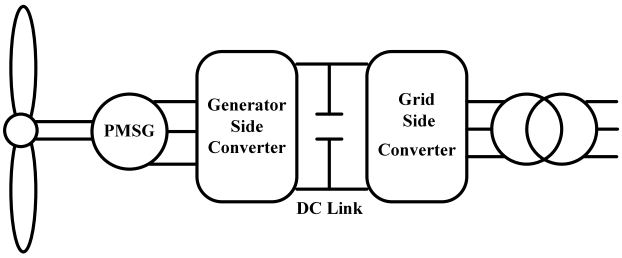

Figure 1. Structure of the wind power generation system

II. MODELING

A permanent magnet synchronous generator (PMSG) based wind power generation system is considered in this study, as shown in Fig. 1.

A fully rated back-to-back converter is used between the grid side and generator side. The control of converters is simple as the generator side converter may be operated in separated with the grid side converter. Hence good performances of the wind power generation system may be achieved, especially in grid fault.

A. Wind Turbine Model

The mechanical power of the wind turbine extracted from the stored power in wind is:

$$P_w = C_p(\lambda, \beta)\frac{1}{2}\rho A {v_w}^3 \tag{1}$$

Where ρ is air density (kg/m^3), A is blades swept area (m^2), C_p is the power coefficient, β is pitch angle (deg) (in this paper $\beta = 0$), v_w is wind speed (m/s) and λ is tip speed ratio. A wind turbine can only extract part of the power from the wind, which is limited by the Betz limit (maximum 59%). This fraction is described as the power coefficient of the turbine C_p, which is depended on the blade pitch angle and the tip speed ratio that may be given by (2) [4].

$$C_p(\lambda, \beta) = (0.44 - 0.0167\beta)\sin\frac{\pi\lambda}{4.775 - 0.3\beta} - 0.0184\lambda\beta \tag{2}$$

The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed .

$$\lambda = \frac{\omega_m R}{v_w} \tag{3}$$

Where ω_m is turbine rotor speed (rad/s) and R is blade radius (m). Thus any change in the rotor speed or the wind speed induces change in the tip speed ratio leading to power coefficient variation. In this way, the generated power is affected. Fig. 2 shows that the mechanical power converted from the turbine blade is a function of the rotational speed, and the converted power is maximized at the particular rotational speed for various wind speed.

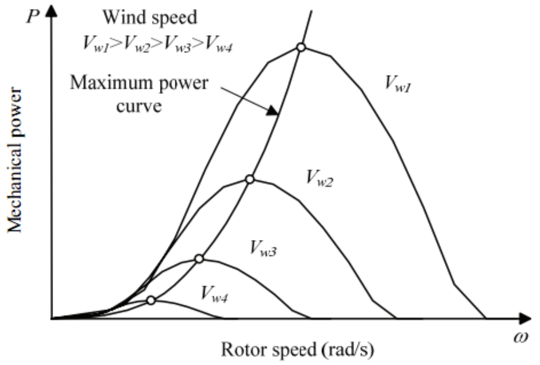

Figure 2. Mechanical power of the wind turbines versus to the rotor speed

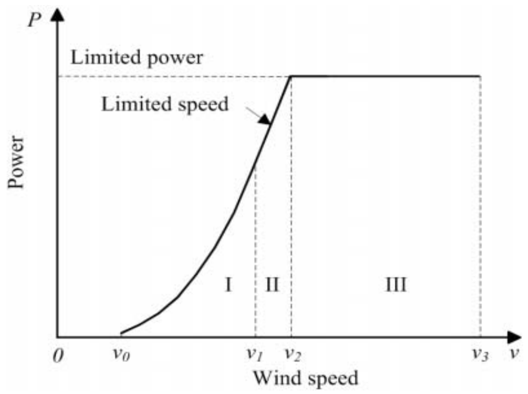

Figure 3. Operation modes of wind turbine

The wind turbine should be driven according to the following three fundamental modes associated with wind speed, maximum allowable rotor speed and rated power.

- Mode I: At below rated wind speed, the efficiency of the turbine is maximized by following maximum power coefficient $C_{p,\max}$ and the wind turbine should continuously operate at the optimal tip speed ratio λ_{opt}. For a given wind speed v_w in order to maintain λ at its optimal value, the rotor speed must be adjusted using a speed controller to track the reference ω_{ref}, which is:

$$ {\omega_m}^{ref} = \frac{\lambda_{opt} v_w}{R} \tag{4}$$

- Mode II: In the intermediate region, rotational speed reaches the limited value with the wind speed increasing. Power coefficient is reduced but captured power still increases.
- Mode III: As wind speed exceeds the rated value, the power extracted from the wind must be limited because of the rated capacity of generator and power converters.

This optimal control trajectory is illustrated in Fig. 3, where v_0 is the cut-in wind speed, v_1 is the wind speed at which the maximum allowable rotor speed is reached, v_2 is the rated wind speed and v_3 is the cut-off wind speed at which the turbine needs to be shut down for protection.

B. Generator Model

The model generally used of the PMSG is the Park model. By considering only the fundamental harmonic of the flux distribution in the air gap of the machine and by neglecting the homopolar component, the theory of the space vector gives the dynamic equations of the stator currents as follows:

$$\begin{aligned} \frac{di_d}{dt} &= \frac{1}{L_s}v_d - \frac{R_s}{L_s}i_d + P\omega_m i_q \\ \frac{di_q}{dt} &= \frac{1}{L_s}v_q - \frac{R_s}{L_s}i_q - P\omega_m i_d - \frac{1}{L_s}P\omega_m\psi \end{aligned} \tag{5}$$

Where v_d and v_q are respectively d axis and q axis voltages, i_d and i_q are respectively d axis and q axis currents, L_s, R_s are respectively generator inductance and resistance, P is the pole pair number, ψ is the magnet flux and ω_m is generator speed that could be obtained from rotor speed with respect to the gear ratio.

The electromagnetic torque is given by:

$$T_e = \frac{3}{2} P \psi i_q \tag{6}$$

The electromagnetic torque equation shows that electrical torque can be directly controlled by q axis current component.

The mechanical dynamic equation is given below:

$$T_e - T_m = J\frac{d\omega_m}{dt} + B\omega_m \tag{7}$$

Where J is rotor inertia, B is friction constant, T_m is the torque produced by wind turbine.

C. Wind Model

A model is required that can properly simulate the spatial effect of wind behaviour :

$$v_{wind} = v_{base} + v_{ramp} + v_{gust} + v_{noise} \tag{8}$$

III. FUZZY CONTROL

A. Fuzzy Logic Controller (FLC)

FLC is one of the most successful applications of fuzzy set theory. Its major feature is the use of linguistic variables rather than numerical variables. The general structure of the FLC is shown in Fig. 4. The FLC is composed of fuzzification, membership function, rule base, fuzzy inference engine and defuzzification [5].

Fuzzification is a mapping from crisp value to fuzzy set according to input membership functions. In fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy IF-THEN rules in fuzzy rule base into a mapping from input fuzzy set to an output fuzzy set [6]. Defuzzification is Also a mapping vice versa fuzzification but according to output membership functions that produces real value, or control action.

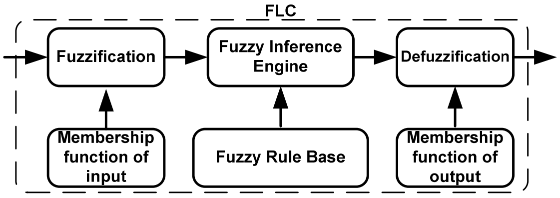

Figure 4. Basic configuration of FLC

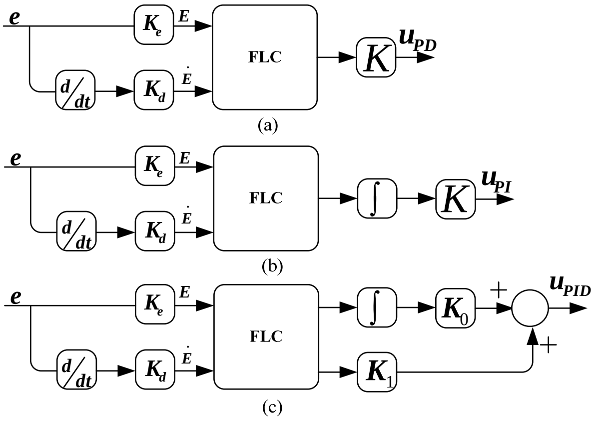

Figure 5. Basic configuration of (a) FZ-PD, (b) FZ-PI and (c) FZ-PID

B. Comparative Design for Conventional FLC

Design and tuning of linear PI/PD/PID controller can be achieved by many systematic approaches and it's a little depend on quantitative knowledge of plant, but in fuzzy control, there is yet no systematic and mature approaches for designing and tuning the scaling gains.

In this paper, we use method that is presented in [3], to designing and tuning the scaling gains. In this method, we obtain the initial parameters of FLC from the parameters of its well-tuned linear counterpart because the well-tuned linear counterpart is often available or could be easier to obtain.

1) Conventional FLC and Its Linear Counterpart: In linear control, PI/PD/PID is three type most beneficial controllers. In fuzzy control, there are also similar PI type FLC (FZ-PI), PD type FLC (FZ-PD), and PID type FLC (FZ-PID) which their basic configuration are shown in Fig. 5.

Here in wind turbine equipped with permanent magnet synchronous generator control, the required linear controller is PI type controller; hence we just study in FZ-FLC to summarization.

2) Fuzzy Linear Control: If a fuzzy controller uses a linear rule base, it is linear in the linguistic domain. This type fuzzy control is defined as fuzzy linear control [3].

TABLE I. A LINEAR RULE BASE

/	NB	NM	NS	ZR	PS	PM	PB
PB	zr	ps	pm	pb	pb	pb	pb
PM	ns	zr	ps	pm	pb	pb	pb
PS	nm	ns	zr	ps	pm	pb	pb
ZR	nb	nm	ns	zr	ps	pm	pb
NS	nb	nb	nm	ns	zr	ps	pm
NM	nb	nb	nb	nm	ns	zr	ps
NB	nb	nb	nb	nb	nm	ns	zr

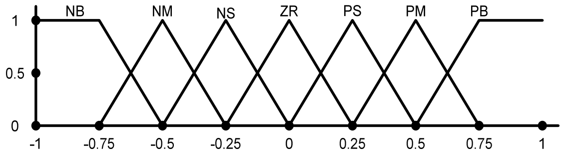

Figure 6. The membership functions for input and output variable

Linear rule base is shown in Table I, it has two dimension and seven labels for each input and output variable fuzzy subset that mean each input and output variable fuzzy subset needs seven membership functions. These seven membership functions must be uniformly distributed triangular that shown in Fig. 6. The membership functions are denoted by NB (negative big), NM (negative medium), NS (negative small), ZR (zero), PS (positive small), PM (positive medium), and PB (positive big).

Control surface of a linear rule base is shown in Fig. 7. Which system stability can be analysis with this three dimensional curve [7].

3) Fuzzy Transfer Function: The fuzzy transfer function $F\{N\}$ between an input variable and an output variable of the fuzzy linear system is defined as the influence of the input scaling gain N on the output. If inputs and the output are normalized into the unity interval [-1, 1], the fuzzy transfer function is assumed to have the following properties [3]:

$$\begin{array}{ll} F\{N\}=1 & \text{when } N>N_{\max} \\ F\{N\}=0 & \text{when } N=0 \\ 0\le F\{N\}\le 1 & \text{when } N\ge 0 \\ F\{N\}<<1 & \text{when } N<<N_{\max} \\ F\{N\}\propto 1 & \text{when } N<<1 \\ F\{\alpha N\}\propto \alpha F\{N\} & \text{when } \max(N,\alpha N)<N_{\max};\alpha\ge 0 \end{array} \qquad (9)$$

Where $N_{\max}$ is the maximum value of the scaling gain for the unsaturated input, and the symbol $\propto$ means the analogy, which can be approximated by $\approx$.

As all inputs and the output are normalized into the unity interval, the maximum influence from the input gain can be assumed to be unity $F\{N\}=1$. It can't be increased for $N>N_{\max}$ because of the input saturation. On the other hand, when the input is not saturated, the influence from the input is proportional to its scaling gain N, and can be approximated as the value of N when N is very small.

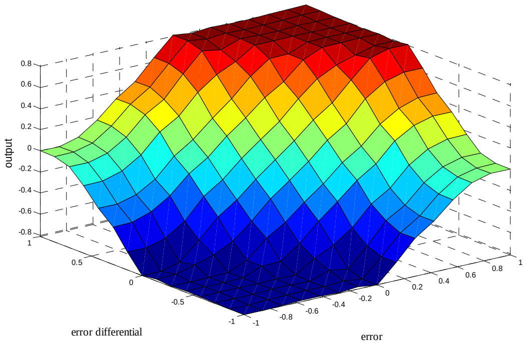

Figure 7. Control surface of linear rule base

C. Comparative Design for FZ-PI

As mentioned above, in our application (wind turbine equipped with permanent magnet synchronous generator control), we just need PI type controller however this fuzzy controller design method is existed for each three PI/PD/PID controller.

1) FZ-PI and Linear PI Controller: In linear control, PI type controller is expressed mathematically as:

$$u_{PI}=K_p e+K_I\int edt=K_p(e+\frac{1}{T_i}\int edt) \qquad (10)$$

Similarly, the conventional FLC should have their own fuzzy proportional gain $\boldsymbol{K_p}$, fuzzy integral gain $\boldsymbol{K_I}$. The fuzzy $\boldsymbol{K_p}$ and $\boldsymbol{K_I}$ of FZ-PI can be expressed with fuzzy transfer function:

$$\boldsymbol{K_p}=KF\{K_d\}$$
$$\boldsymbol{K_I}=KF\{K_e\}=\boldsymbol{K_p}\frac{F\{K_e\}}{F\{K_d\}}=\boldsymbol{K_p}\frac{F\{K_e\}}{F\{\alpha K_e\}} \qquad (11)$$

In the last equation whereas the linear rule base is used, the relationship between two input scaling gains can be approximated as a constant α so $F\{K_d\}=F\{\alpha K_e\}$ [5].

The fuzzy gains ($\boldsymbol{K_p}$, $\boldsymbol{K_I}$) should have qualitative similarity to gains (K_p, K_I) of their linear counterparts.

2) Comparative FZ-PI Gain Design: There is always an input limitation for FLC, so that for convenience inputs and output are always normalized into [-1,1] interval, by dividing by the set point value. For conventional FLC in Fig. 5, two inputs E and $\dot{E}$ are available. The maximum scaling gain for unsaturated E is $K_e=1$. It is not easy to get the maximum scaling gain $K_d=N_{\max}$ for unsaturated $\dot{E}$. Then $F\{K_e\}=1$ and $F\{\alpha K_e\}\le 1$ based on the fuzzy transfer function Definition.

Fuzzy two-term control with a linear rule base is actually a fuzzy linear control, which should have much similarity with its linear counterpart. As fuzzy proportional and integral gains have qualitative similarity with their linear counterparts. The gains (K_p, K_I) of a well-tuned two-term controller in (10) can be used approximately as the initial fuzzy gains ($\boldsymbol{K_p}$, $\boldsymbol{K_I}$) of fuzzy two-term controller in (11).

By the direct comparison between (10) and (11), the analogy between the initial scaling gains (α , K) and gains (K_p, T_i) of linear counterparts can be derived as:

$$K=\frac{K_p}{F\{\alpha K_e\}}\ge K_p$$
$$T_i=\frac{F\{\alpha K_e\}}{F\{K_e\}}\propto\alpha \qquad (12)$$

After a further approximation by replacing $\propto$ with $\approx$, the comparative design for the initial scaling gains of fuzzy PI control can be derived as:

$$\text{FZ-PI} \qquad K = \frac{K_p}{F\{\alpha K_e\}} \geq K_p \qquad T_i \approx \alpha \qquad (13)$$

Thereupon an analogy between scaling gains of fuzzy PI and gains of linear PI can be expressed as:

- The output scaling gain K is more analogous to the proportional gain K_p .
- The input gain ratio α is more analogous to the integral time T_i from PI.

3) Comparative FZ-PI Gain Tuning: According to linear PI controller tuning theory and the relationship is resulted in (13), the influence of scaling gains on PI controller performance could be resulted as:

- Increasing K , similar to increasing $\boldsymbol{K_p}$ in (11), will speed up the response and reduce the steady state error. However, too large K will cause the oscillation or the instability.
- Decreasing α in FZ-PI, similar to increasing $\boldsymbol{K_I}$ in (11), will speed up the response and reduce the steady state error. Too small α will cause large overshoot and tend to destabilize the system.

By the extensive experiments, the heuristic tuning method for designing and tuning fuzzy two-term control are summarized as below:

1. Use gains K_p, T_i of a well-tuned linear two-term control as the initial fuzzy gains $\boldsymbol{K_p}$, T_I the initial scaling gains K_e , α , K can be calculated from (13).
2. Tune K_e , K to achieve a faster response and a smaller steady state error. K_e Should not be too large in order to avoid the input saturation. With $K_e K$ unchanged, adjusting K and K_e can obtain a better control resolution.
3. Tune α to achieve a faster response and a smaller steady state error in FZ-PI.

IV. TOTAL CONTROL STRATEGY

A. Wind Side Converter Control

A block diagram of fuzzy control method implemented on generator side converter is shown in Fig. 8. The controller includes conventional fuzzy PI controller and has advantages of fuzzy controller.

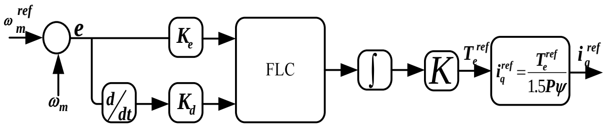

Figure 8. FZ-PI controller and i_q^{ref} creation

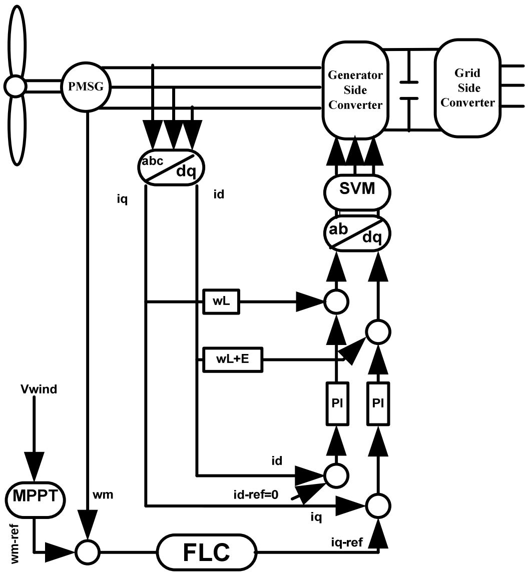

Figure 9. Schematic of control strategy for generator side converter

As shown in Fig. 8, rotor speed reference is obtained from MPPT block then fuzzy control section produce torque reference and q-axis current reference.

Then q-axis current reference is deduced to be controlled by field oriented control section (Fig. 9). The reference value of d-axis current component can be set to zero to minimize current for a given toque and therefore minimize resistive losses.

B. Grid Side Converter Control

A block diagram of grid side converter control is similar to generator side converter control. Active and reactive power is controlling by d and q current components respectively.

V. SIMULATION RESULT

The performance of proposed fuzzy control strategy is evaluated with the simulation study using MATLAB/SIMULINK. Table II shows the wind turbine and generator parameters.

TABLE II. GENERATOR AND WIND TURBINE PARAMETERS

PERMANENT MAGNET SYNCHRONOUS GENERATOR	
Rated Power = 3KW	Pole Pairs = 11
Rated voltage = 220V	Stator flux = 0.5
L_s = 55 mH	R_s = 2.8 Ohm
WIND TURBINE	
Blade Radius = 3.3 m	$C_{p\ max}$ = 0.436
Gear Ratio = 2.09	Rated Wind Speed = 6 m/s

The results are given for a wind speed, shown in Fig. 10. In order to MPPT, the rotor speed of generator must track the reference value which is derived from MPPT section and this purpose is mentioned in Fig.11. So that C_p will approaches to C_{pmax} and it is also verified in Fig. 12.

VI. CONCLUSION

In this paper, a fuzzy controller is presented for maximum power point tracking of wind turbine equipped with PMSG. Through the MPPT algorithm control with fuzzy controller, the highest efficiency of wind generator can be reached, the converters are able to track maximum wind energy.

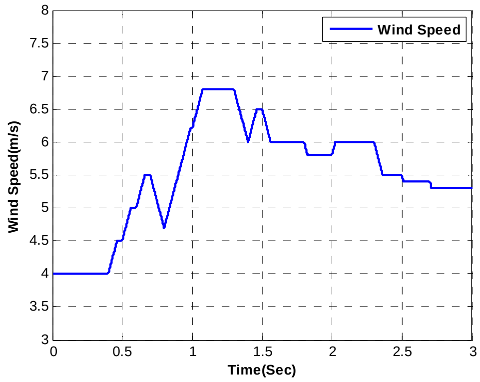

Figure 10. Wind speed

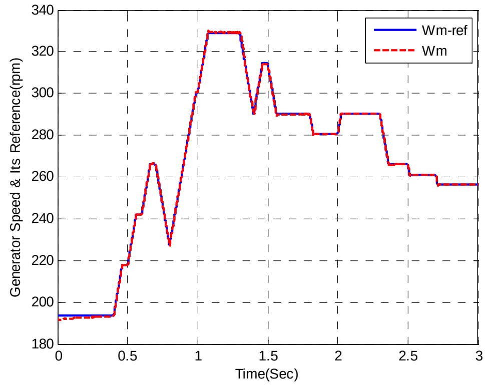

Figure 11. Generator Speed and Its Reference

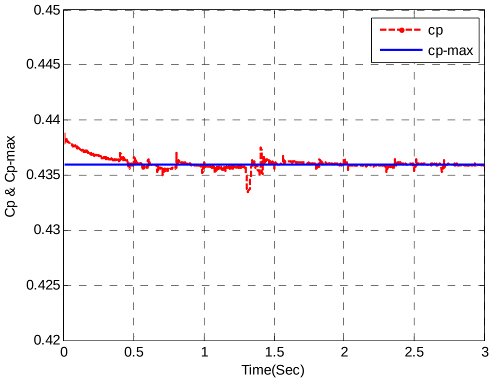

Figure 12. Power Coefficient and Its Maximum

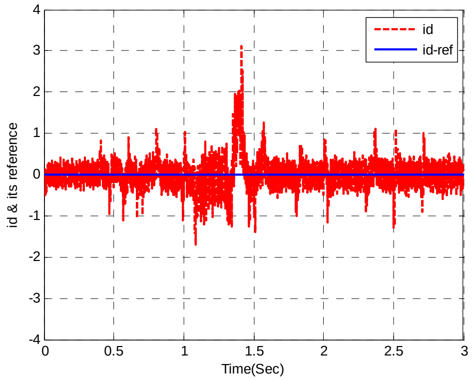

Figure 13. d-axis current and Its Reference

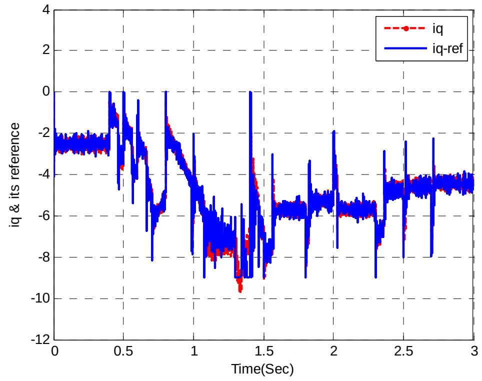

Figure 14. q-axis current and Its Reference

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