

# Fuzzy Logic Based Robust DVC Design of PWM Rectifier Connected to a PMSG WECS under wind/load Disturbance Conditions

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**Abstract** – Permanent Magnet Generator has been widely used in Variable-Speed Wind Energy Conversion System (VSWECS). Fuzzy Logic Control (FLC) of the generator side converter has the ability to have a good regulation of the DC-link voltage to meet the requirements necessary to achieve optimal system operation, regardless of the disturbances caused by the characteristics of the drive train or some changes into the DC-load. The main focus of this paper is to present a model for a three phase voltage source space vector pulse width modulation (SVPWM) rectifier which is connected to a PMSG in a wind turbine system, where a direct voltage control (DVC) using FLC based on voltage orientation strategy is used to control the mentioned rectifier. The control algorithm employs fuzzy logic controller to effectively achieve a smooth control of DC-link voltage under wind/load perturbation conditions. Some simulation results, using Matlab/Simulink, are presented to show the effectiveness of the SVPWM rectifier Connected to a PMSG WECS with the proposed control strategy.

**Keywords:** Direct Voltage Control (DVC); Permanent Magnet Synchronous Generator (PMSG); Wind Energy Conversion System (WECS); Fuzzy Logic Controller (FLC).

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## I. Introduction

Recently, the AC-DC converter applications are increasing in industry, commerce and house utility. Traditionally, the main parts of converters have been the diodes and thyristors bridges to rectify the AC power. These rectifiers have the advantages of being simple, robust and having low cost. However, they generate harmonics and reactive power in AC side, which results voltage distortion, poor power factor at power supply side and slowly varying rippled DC output at DC side. Therefore, a three-phase PWM rectifier is a more cunning solution for industrial applications, since it has more advantages such as adjustment and stabilization of DC-link voltage, sinusoidal line current, power factor control and bidirectional power flow [1]. One of the most considerable industrial applications is wind energy. Nowadays, there are two types of generators which are used in large scale wind turbines to transform the wind power into electrical energy, such as: DFIG and PMSG [2]. Because of its ability to operate in all wind speed range and do not require excitation current, PMSG shows good performance in wind farm. As the fast development of wind power tech

nology [3], the efficiency of converter device in wind power generation system has become another knotty problem to improve wind power generation system performance [2].

The three-phase voltage source PWM rectifier control based on DVC issues are traditionally treated by fixed gain PI controllers [4]. However, the fixed gain controllers are very sensitive to parameter variations and generally cannot provide good dynamic performance, Such as discussed in [5]. So, the controller parameters have to be continually adapted. This problem can be solved by several adaptive control techniques such as sliding mode control (SMC) [6]. The design of all of the above controllers depends on the exact system mathematical model. For the same purpose around solving these problems, the idea that a linear system is adopted as the consequent part of a fuzzy rule has evolved into the innovative Takagi-Sugeno (TS) model [7], which has become quite popular today. The fuzzy logic have gained great important, witnessed a rapid growth in industrial applications, proved their dexterity of many respects. FLC can achieve satisfactory results in dealing with system, which is difficult

to de-scribe mathematically or is highly nonlinear behaviour, as described in [8], [9] which relates to the control of PWM Rectifier whose energy derives from a purely electrical source.

In this paper, a detail dynamic model and a simple direct voltage control (DVC) strategy using fuzzy logic controller for three-phase voltage source SVPWM rectifier connected to a PMSG wind turbine with voltage orientation to improve the system's robustness and dynamic response of the dc bus voltage is proposed. In order to improve the dynamic performances of the source current loop, the simulation results show that the FLC can significantly reduce the three-phase rectifier's voltage fluctuation, improve the dynamic response of the dc-bus significantly and assist the system to operate in unit power factor with low harmonic content of current.

## II. Wind Energy Conversion System

The topology of the WECS presented in this study is depicted in Fig. 1. It consists of a wind turbine, a gearbox, a PMSG, Generator side converter and grid side converter. In our strategy studied, the converter on the generator is used to control the DC link voltage whatever the disturbances caused by the characteristics of the wind turbine drive train or the variation in the DC load.

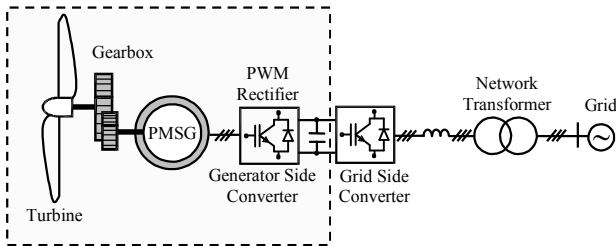


Figure 1. Wind energy conversion chain based on PMSG

The converter on the generator is used to control the DC link-voltage whatever the disturbances caused by the characteristics of the WECS drive train or the variation in the DC load.

### II.1. Aerodynamic subsystem model

The aerodynamic power is dependent on the power coefficient. It is given by [10], [11]:

$$\begin{cases} P_{aer} = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V^3 \\ C_p(\lambda, \beta) = c_1 \left( \frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{-\frac{c_5}{\lambda_i}} + c_6 \lambda \\ \lambda_i^{-1} = (\lambda + 0.08 \beta)^{-1} - 0.035 (\beta^3 + 1)^{-1} \end{cases} \quad (1)$$

Where:  $\rho$  – air density [ $Kg/m^3$ ],  $R$  – blade length

[ $m$ ],  $V$  – wind velocity [ $m/s$ ].

The power coefficient  $C_p$  depends on the ratio  $\lambda$  and the pitch angle  $\beta$  is shown in Fig. 2.

The aerodynamic torque  $T_{aer}$  is calculated by the ratio of the aerodynamic power  $P_{aer}$  to the shaft speed  $\Omega_t$ :

$$T_{aer} = \frac{P_{aer}}{\Omega_t} \quad (2)$$

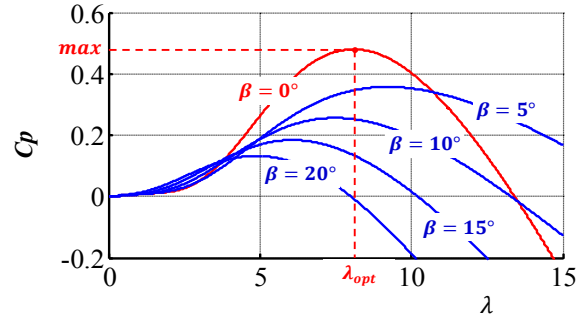


Figure 2. Power coefficient variation against tip speed ratio and pitch angle

The turbine is usually attached to the generator via a gearbox whose gear ratio  $G$  is chosen to adjust the speed of the generator column at the required speed range. The torque and shaft speed of generator are given by:

$$\begin{cases} T_g = T_{aer} G^{-1} \\ \Omega_g = \Omega_t G \end{cases} \quad (3)$$

Where:  $\Omega_g$  – generator shaft speed,  $T_g$  – torque of the generator.

By using the equation (3), the shaft system dynamics can be described as [12]:

$$J \dot{\Omega}_g = T_g - T_{em} - f_v \Omega_g \quad (4)$$

Where:  $T_{em}$  – electromagnetic torque,  $J$  – equivalent inertia,  $f_v$  – viscous friction.

Fig. 3 illustrates a typical characteristic giving the aerodynamic power of a WT-s which is also used in the simulation section. The extractable power is shown versus the rotor speed for different wind speed values. Each diagram for a constant wind speed has a peak value in which the pair  $(\Omega_{g,opt}, P_{aer,max})$  are relevant.

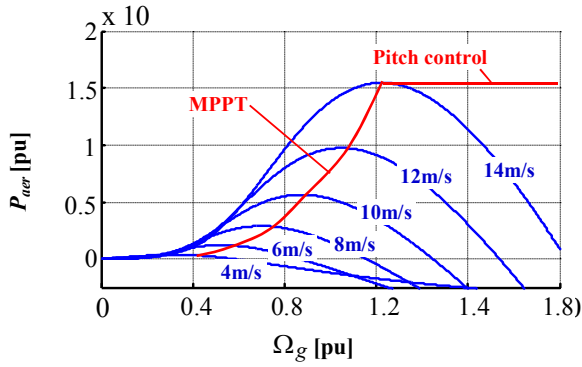


Figure 3. Aerodynamic powers various speed characteristics

### II.2. Electrical subsystem model

The circuit diagram of the three-phase two level voltage source rectifier structure Connected to a PMSG Wind Energy Conversion System is shown in Fig. 4. In order to set up math model, it's assumed that the filter reactor is linear, IGBT is ideal switch and lossless [13].

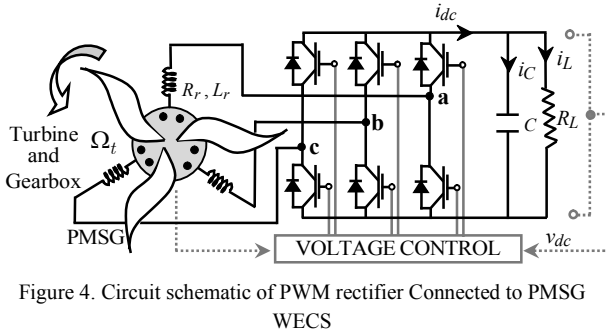


Figure 4. Circuit schematic of PWM rectifier Connected to PMSG WECS

Where  $i_{as}$ ,  $i_{bs}$  and  $i_{cs}$ , are phase currents,  $C$  is smoothing capacitor across the DC bus,  $R_L$  is the load resistance, and  $i_L$  is load current. The classical electrical equations of the PMSG and converter in the PARK frame are written as follows [14], [15]:

$$\begin{cases} v_{ds} = -(R_s + R_r)i_{ds} - (L_s + L_r)\frac{d}{dt}i_{ds} + f_{em,d} \\ v_{qs} = -(R_s + R_r)i_{qs} - (L_s + L_r)\frac{d}{dt}i_{qs} + f_{em,q} \\ C\frac{dv_{dc}}{dt} = (S_d i_{ds} + S_q i_{qs}) - \frac{v_{dc}}{R_L} \end{cases} \quad (5)$$

With  $f_{em,d}$  and  $f_{em,q}$  are the crosses coupling terms between the d-axis and q-axis:

$$\begin{cases} f_{em,d} = \omega(L_s + L_r)i_{qs} \\ f_{em,q} = -\omega(L_s + L_r)i_{ds} + \omega\phi_f \end{cases} \quad (6)$$

Where  $R_s, L_s, R_r, L_r$ , are the stator phase resistance and inductance, the rectifier line resistance and inductance, respectively and  $\omega = \Omega_g p_{pmsg}$  is the electrical

speed and  $p_{pmsg}$  is the pair pole number,  $i_{ds}$  and  $i_{qs}$  are the direct and quadrature stator currents,  $\phi_f$  is magnetic flux.  $S_d, S_q$  are input voltage of rectifier, switch function in synchronous rotating d-q coordinate, respectively and  $v_{dc}$  is the dc-bus voltage.

The electromagnetic torque is expressed as [16]:

$$T_{em} = \frac{3}{2} p_{pmsg} \phi_f i_{qs} \quad (7)$$

### III. Direct Voltage Control (DVC) Strategy

In this section, the principle of this control (DVC) based on voltage orientation consists of using a current loop, developed by analogy with the vector control of electrical machines. It consists of orienting the current vector in the same direction as that of the voltage vector, by controlling the current vector in the two revolving d-q axes. Regarding Fig. 5, the current of the d-axis is set to zero while the reference current  $i_{qs}$  is set by the DC link voltage regulator.

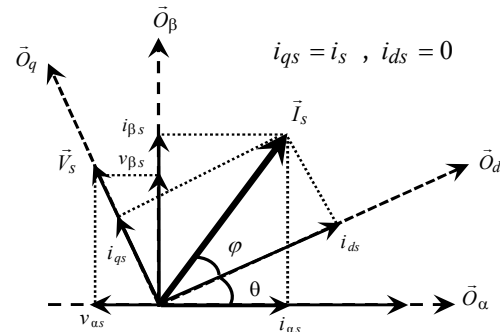


Figure 5. Voltage orientation

Once the rectifier is connected to an existing load, the transit of direct and quadrature axis currents must be controlled separately. To obtain a decoupled currents control of rectifier, the method based on voltage orientation can be regarded as the efficient one.

There are three control loops in the DVC strategy. The error between the reference dc-bus voltage  $v_{dc}^*$  and the sampled dc-bus voltage  $v_{dc}$  is processed by FLC, which produces the reference active current  $i_{qs}^*$ . As in the inner loops, d-axis currents loop and q-axis current loop use PI controllers to make the actual currents ( $i_{ds}$  and  $i_{qs}$ ) track their reference values ( $i_{ds}^*$  and  $i_{qs}^*$ ). Then, the errors are processed in two conventional PI controllers to produce the output signals of  $v_{ds}^*$  and  $v_{qs}^*$ , after coordinates transformation,  $v_{sa}^*$ ,  $v_{sb}^*$  and  $v_{sc}^*$

which can be obtained and used to produce switching signals  $S_a, S_b$  and  $S_c$  by two-level space vector pulse with modulation (SVPWM).

Consequently, the proposed currents control can then be applied, as depicted in Fig. 6, Considering that the direct and quadrature axis currents considered as variables to be controlled.

With:  $A_s = 1/(R_r + R_s)$ ;  $T_s = 1/(L_r + L_s)$

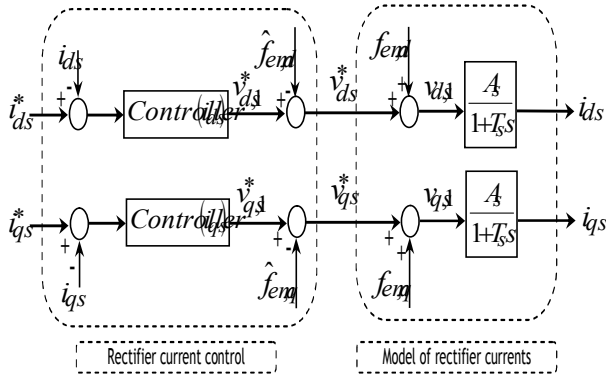


Figure 6. The block diagram of direct and quadrature axis currents control

## IV. Controller Design

### IV.1. PI regulator synthesis

In order to control the converter used, we must perform a decoupling by compensation. To make the “d” and “q” axes completely independent. The parameters of the corrector are calculated with a method of imposition of the poles. It is possible to generate reference voltages from given reference quantities. The design of this controller is simple. Fig. 7, 8 shows the system scheme regulated by a PI corrector.

Consequently, the proposed currents control can then

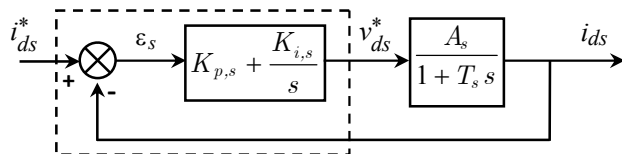


Figure 7. Direct current regulation loop

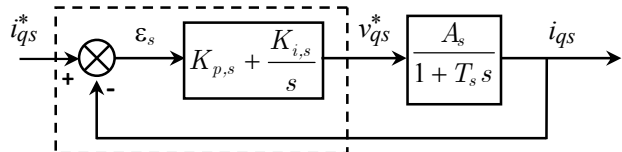


Figure 8. Quadrature current regulation loop

In fact, the errors  $(i_{ds}^* - i_{ds})$  and the errors  $(i_{qs}^* - i_{qs})$  are processed by the PI corrector, in order to design the

reference voltages  $v_{dq,s}^*$ . Using the Laplace transformation, the closed-loop transfer function is given as follows:

$$CLTF = \frac{\frac{A_s}{T_s}(K_{p,s}s + K_{i,s})}{s^2 + s\left(\frac{1 + A_s K_{p,s}}{T_s}\right) + \frac{AK_{i,s}}{T_s}} \quad (8)$$

The calculated terms are in these tables:

TABLE 1. The calculated PI gains

	$K_{p,s}$	$K_{i,s}$
PI controller	$(2T_s\xi\omega_0 - 1)/A_s$	$T_s\omega_0^2/A_s$
Value	150	10

### 4.2. Fuzzy Logic Controller (FLC)

To regulate the DC voltage, FLC is used because of the nonlinearity of the system. The basic formation of a FLC is consisted of four parts: Fuzzification block determining inputs membership values. The Fuzzy Inference System FIS evaluates at each time which control rules are appropriate, using the fuzzy knowledge based block. The defuzzification block calculates the crisp output of the rules leading to the optimal plant control [17, 18]. Fig. 9 shows the block diagram of the fuzzy control.

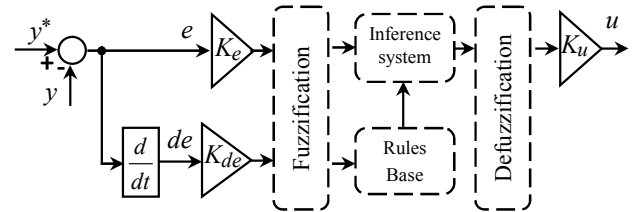


Figure 9. Fuzzy logic controller structure

The input and output linguistic variables of the fuzzy controller have been quantized in the following five fuzzy subsets. Where the error  $e$  and its rate of change  $de$  are the input variables;  $K_e$ ,  $K_{de}$  and  $K_u$  are inputs and outputs scaling gains. For the proposed FLC of DC link voltage, we use diagram scheme of Fig. 10.

TABLE 2. Fuzzy rule-base for the controller

		$\varepsilon$				
		NL	NS	ZE	PS	PL
$d\varepsilon$						
NL		NL	NL	NL	NS	ZE
NS		NL	NS	NS	ZE	PS
ZE		NL	NS	ZE	PS	PL
PS		NS	ZE	PS	PS	PL
PL		ZE	PS	PL	PL	PL

There are two input signals to the FLC; the first input is the error between the reference and the measured value of the DC voltage, the second one represents the varia-

tion of this error. These two signals are expressed by:

$$\begin{cases} e_{dc}(n) = v_{dc}^*(n) - v_{dc}(n) \\ \Delta e_{dc}(n) = v_{dc}^*(n) - v_{dc}(n-1) \end{cases} \quad (9)$$

### V. Results and discussion

The fuzzy sets have been determined as: NL, Negative Large, NS, Negative Small and ZE, Zero, PS, Positive Small, PM positive medium, PL, Positive Large, respectively. The input/output variables used in this paper are fuzzified by seven symmetrical and triangular membership functions (MFs) (Fig. 10(a), (b) and (c)) normalized in the universe of discourse between -1 and +1. The FLC surface is depicted in Fig. 10(d). Then, the outputs of the DC-link voltage fuzzy controller are  $i_{qs}^*$ .

Finally, the overall simulation scheme of a three phase PWM Rectifier under DVC strategy connected to a PMSG WECS is given in Fig. 11.

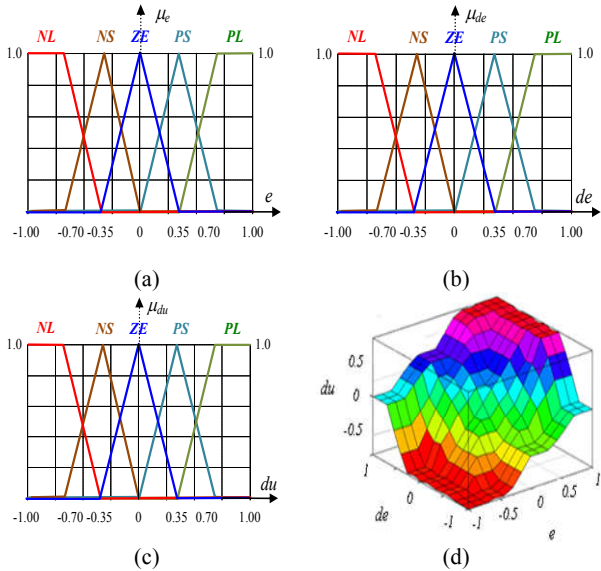


Figure 10. The memberships of: (a) – Error, (b) - Error variation, (c)- Command variation, (d) - Control surface

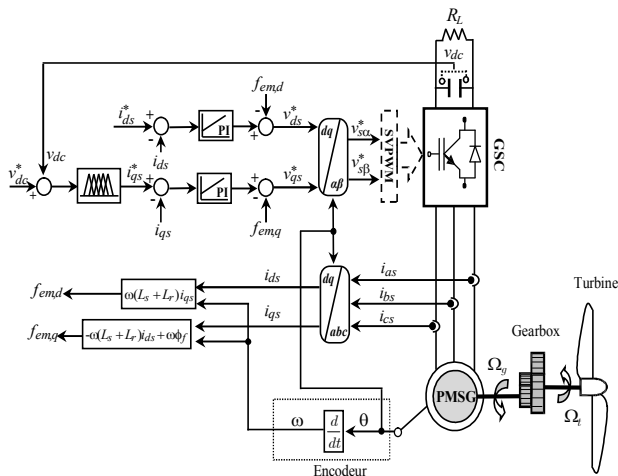


Figure 11. The block diagram of the proposed DVC approach  
 Fig. 12a shows the input phase current of SVPWM-rectifier. As can be seen in this figure, the current wave has a sinusoidal shape with very low harmonic distortion. The FFT analysis is applied to the line current of phase A of the rectifier. This analysis gives 0.62 [pu] as an effective value for the fundamental component of line current (THD about 2.25%) that is shown in Fig. 12b, is improved when compared to conventional voltage orientation technique (THD=16.06%) [5]. So, It is found that most of the harmonics are low ranks.

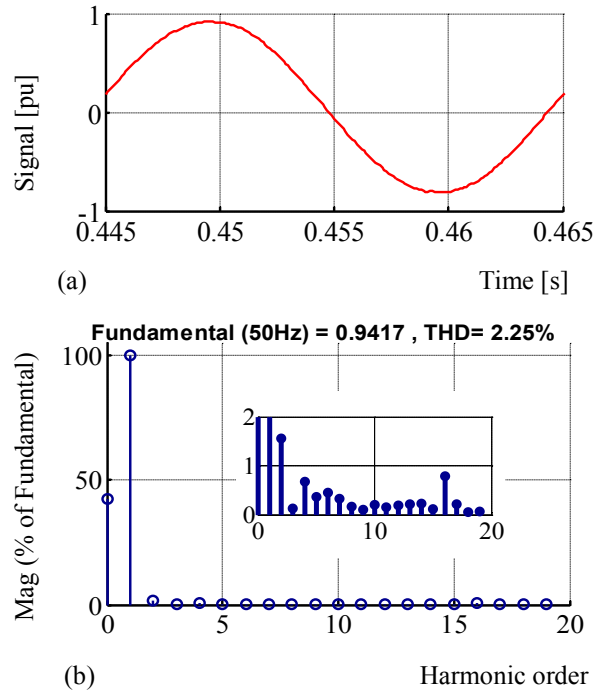


Figure 12. Harmonic spectra of line current of phase A of the rectifier

All the simulation results were elaborated with a fixed-step size of 0.1 [ms] with a view to digital implementation in future works.

Three tests are under study to prove the robustness dynamic response of the proposed DVC approach, firstly the variation on the wind speed (9 to 7 [m/s]) at  $t=0.5[s]$  as shown in Fig. 13a, then the variation on the reference voltage of DC link (0.8 to 1 [pu]) at  $t=1[s]$  is shown in Fig. 13c and DC load resistance variation (500 to  $5*500[\Omega]$ ) at  $t=1.5[s]$  is seen in Fig. 13b.

Fig. 13c shows the output DC voltage. As can be seen in this figure, the DC-Link voltage, after a short transient time, is correctly regulated at its reference voltage (0.8 then 1 [pu]) with soft regulation without over-hoots. The mechanical speed of the PMSG shaft is given in Fig. 13d, it is clear that it takes the same shape as the wind speed.

The electromagnetic torque is shown in Fig. 13e, with a negative value, which proves that the machine used functions as a generator. Fig. 13f shows the setting of direct and quadrature axis currents. The d-axis current is maintained at its zero reference value, while the q-axis current regulation is done by reference DC-voltage control. However, the effect of the coupling between the two control axes (d and q) is observed, since the variation on the reference DC voltage at time  $t=1[s]$  induces low oscillation on the d-q axis currents.

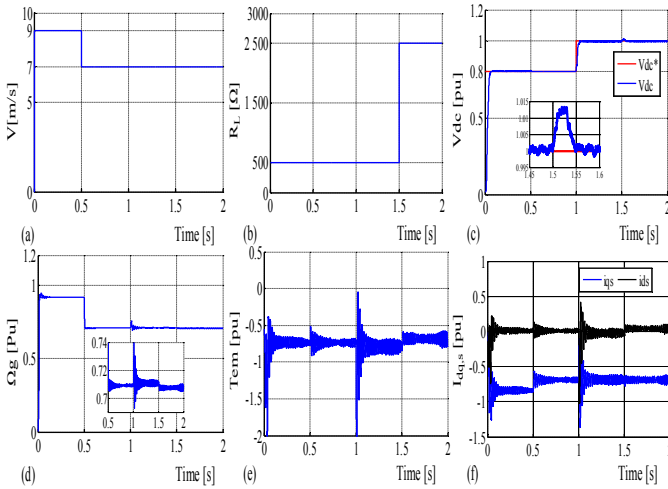


Figure 13. Simulation results: (a) Wind speed profile, (b) Load resistance variation, (c) DC-Link voltage, (d) Generator speed, (e) Electromagnetic torque, (f) d-q axis current

## Appendix

In this part, simulations are investigated with a 1.5 MW generator wind turbine [19]. The parameters of the turbine are presented below:

Turbine	PMSG	Rectifier
$\rho = 1.22 \text{ Kg} / \text{m}^3$	$P_{sn} = 1.5 \text{ MW}$	$R_r = 37 \text{ mH}$
$R = 35.25 \text{ m}$	$p_{pmsg} = 80$	$L_r = 0,3 \Omega$
$\beta = 0 \text{ deg}$	$R_s = 3.17 \text{ m}\Omega$	$C = 1100 \mu\text{F}$
$G = 30$	$L_s = 3.07 \text{ mH}$	
	$\phi_f = 7.0172 \text{ Wb}$	

## VI. Conclusion

A cascaded control algorithm was properly designed to ensure the optimal operation of the whole system, based on fuzzy logic controller (FLC) with voltage orientation technique. Furthermore output DC link voltage is smooth despite a wind/load fluctuation. The control system based on DVC includes two PI controllers which are

used to regulate the AC current and an outer DC voltage loop is composed by FLC strategy.

The simulation results shows a good performance and a robust control of DVC proposed method at start-up and during wind/load variations, providing a good regulation of output DC voltage, sinusoidal AC current and low total harmonic distortion. It can be concluded from the simulation results, which demonstrate the inherent ability of the DVC fuzzy logic controller to deal with this kind of noise operation under wind/load disturbance conditions.

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