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DYNAMIC STABILITY ENHANCEMENT OF WIND ENERGY CONVERSION SYSTEM USING ADAPTIVE CONTROL STRATEGY

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ABSTRACT

Modern wind power applications require efficient and flexible control strategy that adapt themselves to the changes in load and other disturbance. The interaction of grid and its impact on wind turbines have been in focus over the years. The wind turbines, among the various distributed generation system are considered to be potential sources of power quality issues due to the dynamic changes in the wind turbine operations. This paper presents an adaptive PI control strategy to stabilize the dynamics of Wind Energy conversion system (WECS) and to improve the grid voltage profile during post fault conditions. The dynamic performance of wind system is improved by a self-tuned control strategy at the transmission side. A new technology for tracking are adapted to extract the maximum power from the available wind by considering the uncertainties occurring in wind speed.

KEYWORDS: Adaptive PI control, Dynamic performance, Wind Energy conversion system (WECS), Maximum tracking point, Permanent magnet Synchronous generator, PWM-current source converter.

I. INTRODUCTION

WIND energy is an important source of electrical energy over the years, being a renewable and environmental-friendly energy. Earlier the wind power generation was limited to few hundreds of kilowatts, supplying to an isolated area/load with permissive power quality issues. With the growth of Wind turbines and farms in size and ratio from the few hundred kilowatts to megawatts size, endures them to integrate with the grid which leads to the new problems such as interface of wind farms with the grid [1].

In general most of the wind energy systems employ induction generators because of high efficiency & good controllability. In this paper the permanent magnet synchronous generators are employed due to their high power density & enables the grid integration by means of pulse width modulated current source converter(PWM-CSC) which has advantage of controlling the DC current according to the wind velocity irrespective of DC voltage rather than a conventional voltage source converter [2]. Most of the contribution made in the area of wind energy conversion system control is by using conventional regulators which has certain limitations such as, the system identification and the calculation of the controller parameters have to be done offline, which leads to uncertainties in model prediction & may cause poor dynamic response [3].

The proposed control strategy implements an adaptive PI controller which is a self-tuned based on the power system state calculated at a regular sample time. The proposed control technique is a good alternative due to its high efficiency and can handle complex systems that have unpredictable parameter deviations & uncertainties.

Proportional Resonant & proportional integral controllers have been widely used for control of power systems. Tuning of these controller parameters is highly demanding tasks when the system is time invariant.

II. WIND ENERGY CONVERSION SYSTEM

In the proposed system, a permanent magnet synchronous generator is used instead of a doubly fed induction generator because of various advantages such as high power density and soft start due to magnetization provided by the permanent magnets, also because of insignificant losses in the rotor and less reactive power compensation. Different possible configurations of PMSG used in wind energy conversion system are shown in Fig.1.

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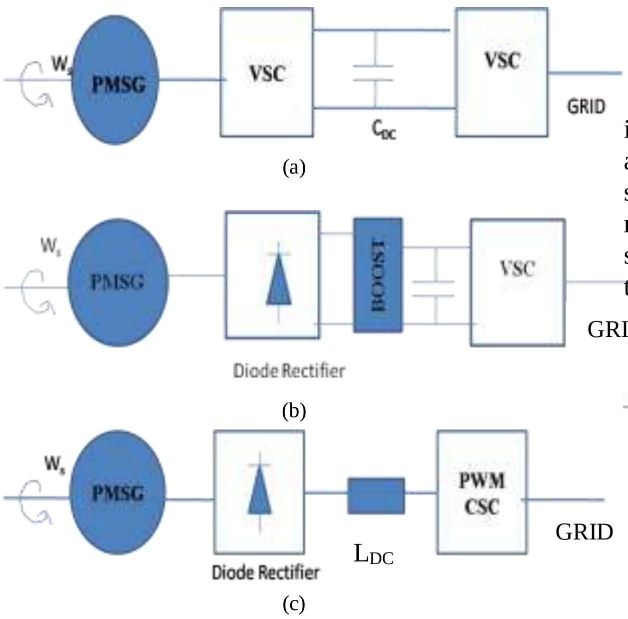

Fig.1. Three possible configurations for PMSG integration: (a) back to back converter with VSCs, (b) Diode-bridge rectifier and boost converter and (c) Proposed energy conversion system with PWM-CSC.

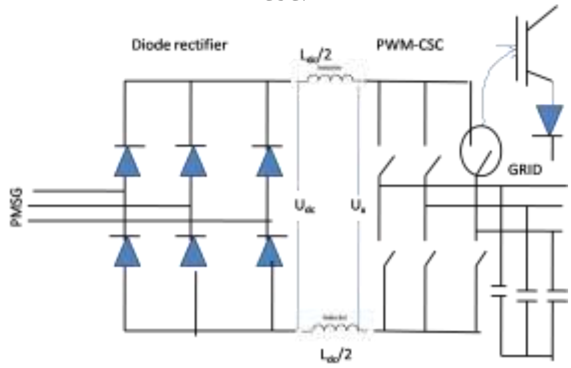

Fig.2. Pulse-width modulated current source converter

Since the machine does not require reactive power compensation the output terminals of PMSG can be connected to a simple diode rectifier as shown in Fig.2 since the machine does not require reactive power compensation. This has to be connected to a full rated back to back converter. For a PMSG machine with a voltage source converter the DC voltage must remain within certain limits in order to maintain stability constraints. For this purpose a DC-DC boost converter is employed to control the power in the electrical circuit [4].

Another option is to integrate the PMSG with a PWM-current source converter. Power electronic devices mainly consist of two types of losses such as switching losses & conduction losses.

Whenever a full bridge is considered the switching losses can be avoided only conduction losses persists since switching occurs only once in a full cycle [5].

III ADAPTIVE PI CONTROL STRATEGY

The new controlling technique can be adapted to integrate the PMSG based wind turbine into the grid as depicted in Fig. 5 includes an adaptive control strategy which is as shown in Fig. 3, extraction of maximum tracking point using a suitable algorithm as shown in Fig. 4. It produces I_{DC} dynamically according to the variations in wind velocity

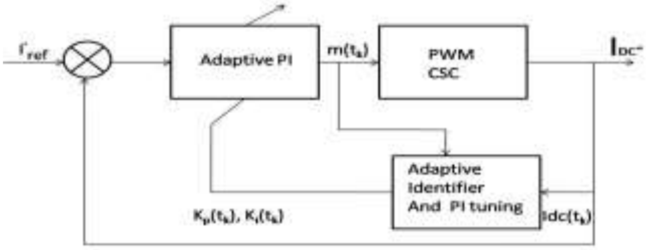

Fig. 3. Adaptive control and identifier.

A *Maximum Tracking Point*

The PMSG machine coupled to wind turbine generates power which is proportional to the cube of the wind velocity as given in equation (1):

$$P = 1/2 * \rho . A C_P(\lambda, \beta) V^3 \qquad (1)$$

The optimal value of tip ratio λ achieves maximum power transference. Here consequently the rotational speed must be proportional to the wind velocity and hence, power must be Proportional to the cube of the rotational speed as given in equation (2):

$$P_{pu} = \frac{P(t)}{P_{nom}} = \omega_s^{\,3}(pu) \qquad (2)$$

On the other hand, the PMSG is modeled on the rotor reference frame as follows:

$$u_s(d) = R_s i_s(d) + L_s . \frac{d}{dt} i_s(d) - L_s . \omega_s . i_s(q) \qquad (3)$$

$$u_s(q) = R_s i_s(q) + L_s . \frac{d}{dt} i_s(q) + L_s . \omega_s . i_s(d) + \psi_m . \omega_s \qquad (4)$$

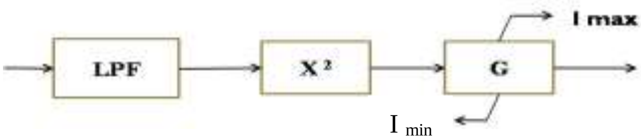

Fig. 4. Reference for using a maximum tracking point algorithm.

The voltage on the diode rectifier (see Fig. 2) is proportional to the voltage in the terminals of the machine which in turn is given by equation (5)

$$U_{DC} = \Phi . \omega_s \qquad (5)$$

where Φ is a proportional constant.

This approximation will be demonstrated numerically on Section IV. This expression involves measurement of voltage which does not require a speed sensor. It is obtained by replacing equation (2) in the rotor reference frame model of PMSG by ignoring the voltage drop in the inductance. The generated power is given by (PMSG losses are ignored). As a result, the optimal to achieve maximum tracking is given by equation (6):

$$I_{dc}(t) = G.(U_{DC}(t))^2 \qquad (6)$$

where is G a proportional value which can be approximated as follows:

$$G = \frac{P_{nom}}{U^2{}_{DC(nom)}} \qquad (7)$$

This equation establishes a set point for current as given in Fig. 3. A low pass digital filter (LPF) is required to smooth voltage. The cut-off frequency is set below commutation frequency. On the other hand, the dynamics of depends on the inductance as follows:

$$U_{DC}(t) = L_{DC}\frac{d}{dt}I_{DC}(t) + U_x(t) \qquad (8)$$

Each element in this equation is given in Fig. 2. The modulation of the converter depends on the current which varies according to the wind velocity but cannot be zero. Therefore, equation (8) can be written in terms of power as given in equation(9):

$$P(t) = \frac{L_{DC}}{2}\frac{d}{dt}I_{DC}{}^2(t) + P_x(t) \qquad (9)$$

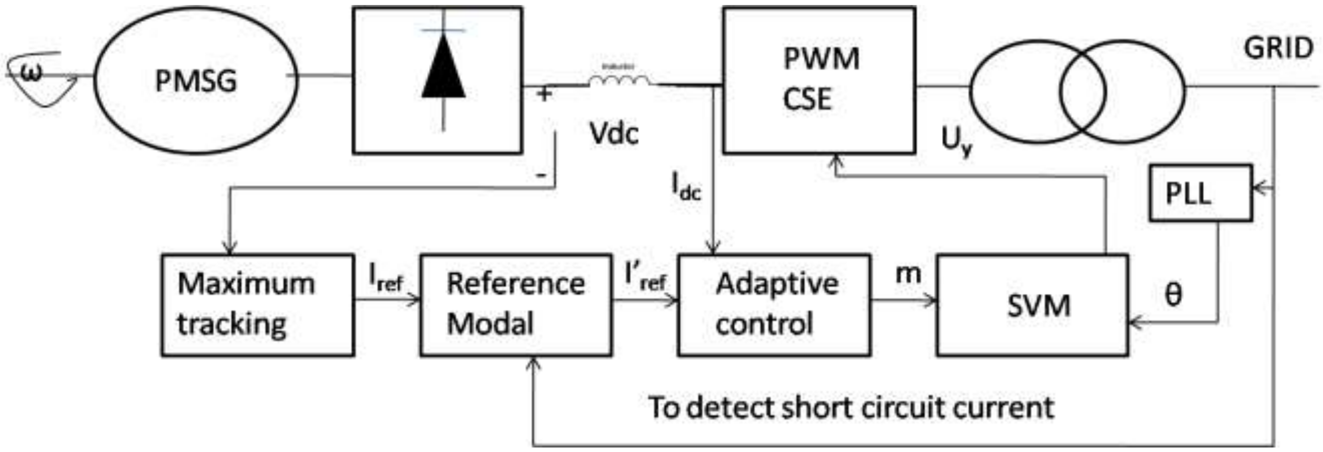

Fig. 5. Proposed hierarchical strategy for adaptive control of the energy conversion system based on a pulse-width modulated current source converter.

Where P(t) is the power delivered by the converter which inturn depends on the modulation index. Therefore the control variable is as given in equation (10):

$$P_x(t) = m(t).I_{DC}(t).U_y(t) \qquad (10)$$

A phase locked loop is required to make the angle of output current equal to angle of the grid voltage in order to have unity power factor. The output power beyond the capacitive filter is approximately equal to P_x. Usually, the control in current source converters is made in two stages, one controlling the active power and the other controlling the voltage in the AC side.

Active power is controlled by this approach on the other hand modulation maintains the reactive power. With this the possible resonances on the controls can be reduced. In the next subsection the implementation of adaptive controlling technique to the resulting nonlinear system will be discussed.

B Adaptive Control

An adaptive controller is a fixed structure controller with adjustable parameters and a mechanism to automatically adjust those parameters. In this sense an adaptive controller is one way of dealing with parametric uncertainty Adaptive control theory essentially deals with finding parameter adjustment algorithms that guarantee global stability & convergence. This paper means that any control strategy which uses parameter estimation of the plant in real time utilizes recursive identification approach. The adaptive controller to be designed is based on the certainty equivalence principle: design the controller as long as the plant parameters are known. However, since these are unknown at time, they are replaced by an estimate given by an online identifier [23].

An adaptive controller will contain characterization of desired closed-loop performance (reference model or design specification. A controlled plant requires only the output signal for its feedback, which makes the design of the adaptive controller easy. The plant parameters are estimated by using an online identifier as shown in Fig. 3.

In continuous time, a PI controller can be defined as

$$u(t)=K_P e(t)+K_i\int_0^t e(\tau)d\tau \qquad (11)$$

being u(t) the control signal, and e(t) the error signal (represented by the difference between the reference and the output signals). In this case, these variables are given as follows

$$e(t)=I'_{ref}(t)-I_{DC}(t) \qquad (12)$$
$$u(t)=-m(t).U_x(t).I_{DC}(t) \qquad (13)$$

(

In discrete time, the PI controller can be defined:

$$e_i(t_k)=e_i(t_{k-1})+e(t_k) \qquad (14)$$
($$u(t_k)=K_p e(t_k)+K_i e_i(t_k) \qquad (15)$$

Obtaining the following expression for the PI controller in discrete time

$$u(t_k)=\frac{c_1+c_2q^{-1}}{1-q^{-1}}e(t_k) \qquad (16)$$

where the parameters of the PI controller in continuous time can be related to the controller in discrete time, as follows:

$$K_p=-c_2 \qquad (17)$$
$$K_i=\frac{c_1+c_2}{h} \qquad (18)$$
$$y(t_k)=\frac{b_0q^{-1}}{1+a_1q^{-1}}u(t_k) \qquad (19)$$

The equations are used to formulate the block diagram

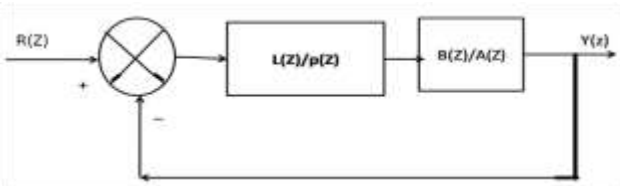

Fig. 6. Diagram block using Z transformation

From the Fig.6 it is possible to obtain the closed loop transfer function, as follows:

$$Y(z)=\frac{B(z)}{A(z)}U(z) \qquad (20)$$
$$U(z)=\frac{L(z)}{P(z)}E(z) \qquad (21)$$
$$E(z)=R(z)-Y(z) \qquad (22)$$
$$Y(z)=\frac{B(z)L(z)}{A(z)P(z)+B(Z)L(z)}R(z) \qquad (23)$$

If defining desired closed loop poles, given by

$$P_d(Z)=\left(1-\alpha_1z^{-1}\right)\left(1-\alpha_2z^{-1}\right) \qquad (24)$$

where α_1 and α_2 are the discrete time roots of (34), which can be related to the continuous time roots s_1 and s_2 by using equations (25) and (26)

$$\alpha_1=e^{s_1h} \qquad (25)$$
$$\alpha_2=e^{s_2h} \qquad (26)$$

The controller parameters can be obtained by comparing the closed loop poles with the desired closed loop poles as follows:

$$P_d(z)=A(z)P(z)+B(z)L(z) \qquad (27)$$
$$P_d(z)=1-(\alpha_1+\alpha_2)z^{-1}+\alpha_1\alpha_2z^{-2} \qquad (28)$$

Therefore, the controller parameters can be obtained as follows

$$c_1=\frac{(-\alpha_1-\alpha_2-a_1+1)}{b_0} \qquad (29)$$
$$c_2=\frac{(\alpha_1\alpha_2+a_1)}{b_0} \qquad (30)$$

When the projection algorithm is applied then the following actualization rule is obtained:

$$(t_k)=-a_1(t_{k-1})y(t_{k-1})+b_0(t_{k-1})u(t_{k-1}) \qquad (31)$$
$$a_1(t_k)=a_1(t_{k-1})+\frac{-y(t_{k-1})}{y(t_{k-1})^2+u(t_{k-1})^2}(y(t_k)-\hat{y}(t_k)) \qquad (32)$$
$$b_0(t_k)=b_0(t_{k-1})+\frac{u(t_{k-1})}{y(t_{k-1})^2+u(t_{k-1})^2}y(t_k)-\hat{y}(t_k) \qquad (33)$$

Since the controller parameters are dependent on a_1 and b_0 and according to (29), a time varying parameters for each can be obtained as follows

$$c_1(t_k)=\frac{(-\alpha_1-\alpha_2-a_1(t_k)+1)}{b_0(t_k)} \qquad (34)$$
$$c_2(t_k)=\frac{(\alpha_1\alpha_2+a_1(t_k))}{b_0(t_k)} \qquad (35)$$

where C_1 and C_2 are automatically tuned according to the desired closed loop poles.

Finally, the controller parameters and can be calculated from equation (17) by

$$K_p(t_k)=-c_2(t_k) \qquad (36)$$
$$K_i(t_k)=\frac{c_1(t_k)+c_2(t_k)}{h} \qquad (37)$$

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From this ,the adaptive controller is calculated for each time t_k . The behavior of the controller can be determined by the selection of the desired closed loop poles of equation (24) and the sample time h , according to equation (25).

C. Model Reference Adaptive Control

The objective of MRAC is to find the feedback control law that changes the structure and dynamics of the plant so that its I/O properties are exactly the same as those of the reference model.Reference current is modified during a short circuit in order to improve the short circuit behavior of the converter. A slightly different current in which the desired output is generated by a linear reference model is proposed [26].

The reference model can be selected with an order less than or equal to the order of the process. In this work, a zero order model is used in pre-fault, no control during the fault and a first order model after the fault as follows:

$$I'_{ref} = H_m(z) I_{ref} \qquad (38)$$

$$H_m(z) = \frac{(1-\rho_0)z^{-1}}{1-\rho_0 z^{-1}} \qquad (39)$$

Where ρ_0 must be selected as a stable root , where it is clear that the reference model must be selected as a stable model with unitary gain. In MRAC, a good understanding of the plant and the performance requirements it has to meet allow the designer to come up with a model, referred to as the reference model, that describes the desired I/O properties of the closed-loop plant [27].

Under disturbance conditions to improve the performance of the converter a model reference is needed. The pole placement techniques and the selection of the suitable reference model are regarded as separate problems. The reference model gives the error input to the adaptive controller which is the difference between reference current and I_{DC} as shown in Fig.7.The tuning of PI controller can minimize this error.

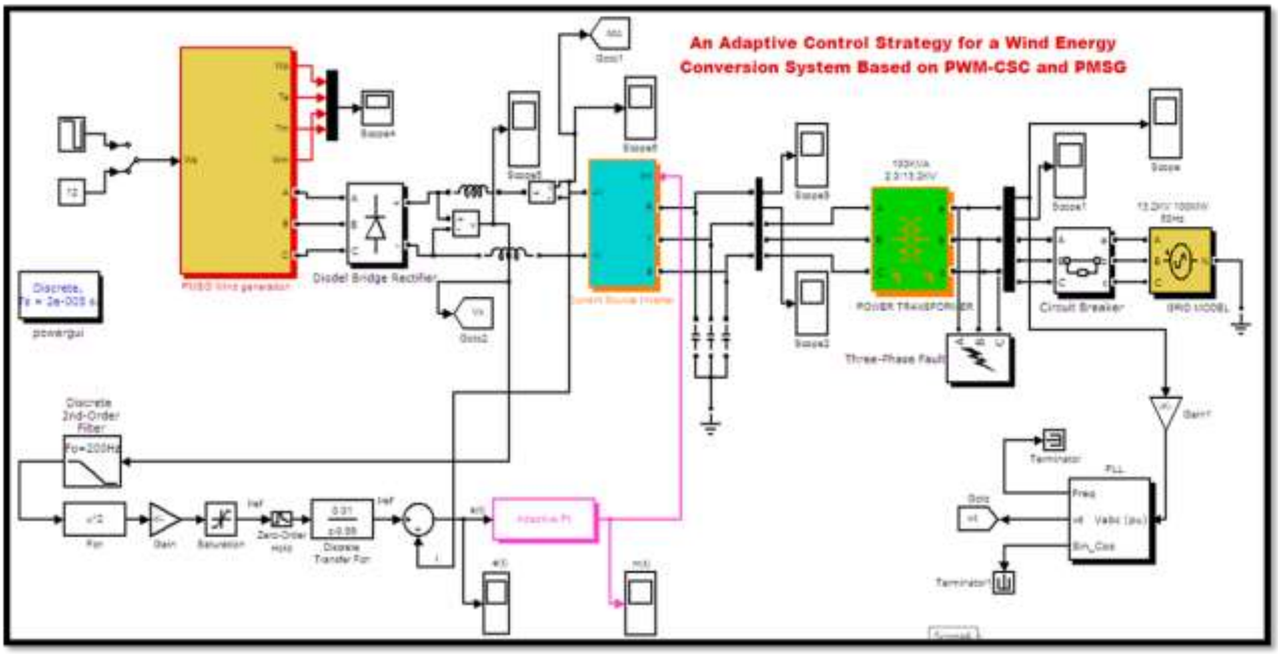

Fig. 7.Simulation block diagram of adaptive control based WECS

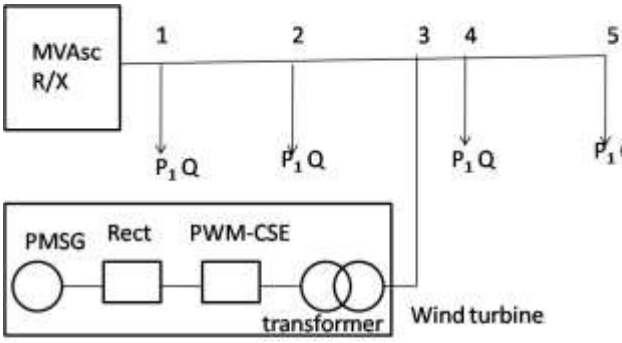

Fig.8. Simulated primary feeder with the proposed energy conversion system.

TABLE I
PARAMETERS OF THE SYSTEM

Parameter	Value	Unit	Component
Nominal power	2	MVA	
Nominal voltage	690	V	
Nominal rotational speed	$2\pi 34$	rad/s	
Stator phase resistance	0.05	pu	PMSG
Armature impedance	0.80	pu	
Flux	1.50	pu	
Nominal wind velocity	12	m/s	
Nominal power	2	MW	Turbine
Inertia constant	1.27	s	
Nominal DC current	2	kA	
Switching frequency	1	kHz	PWM-CSC
Nominal voltage	13.2	kV	
Three-phase short circuit power	100	MW	Grid
Cut-off frequency	200	Hz	AC filter
X/R ratio	7		
Frequency	60	Hz	
α_1	0.8		
α_2	0.8		Control
ρ_o	0.99		
h	1	ms	

so it is evident that by using a reference model the flexibility of the control system in the assignment of the closed loop poles is increased. The fault condition is detected using the U_x [1].

IV RESULTS

A detailed switching model of the proposed energy conversion system was simulated using Matlab-Simulink. The system consists of a 13.2-kV distribution feeder with a 2-MWwind turbine as shown in Fig. 7. Parameters of this system are shown in Table I.

The discrete time roots were selected in order toachieve steady state in 20 ms. On the other hand, the reference model for short circuit condition was calculated for 400 ms. Wind velocity for 5-s simulation is depicted in Fig. 8. Base wind velocity is 12 m/s. A gust is simulated in order to demonstrate the maximum tracking point capability of the proposed control. Wind velocity profile was created using a detailed model which considers stochastic behavior [24]. Rotational speed and voltage are plotted in Fig. 8. These two variables are proportional as expected. Fig. 9 shows voltage with respect to rotational speed for the aforementioned simulation. The linear approximation given which is more accurate for low wind velocities. At high wind velocities, the generated power increases the current and hence, the voltage drop on the inductance influences the generated voltage. Nevertheless, the linear approximation is accurate enough from a practical point

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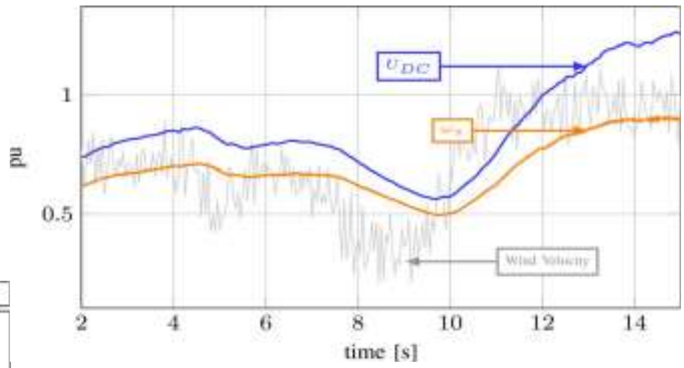

Fig. 9. Wind velocity, rotational speed and DC voltage .

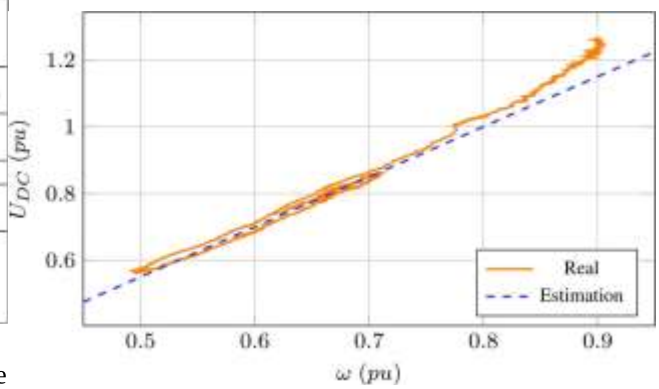

Fig. 10.Voltage versus rotational speed.

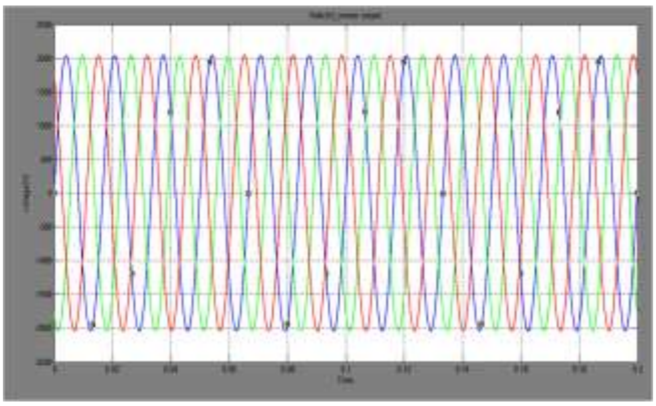

Fig. 11. Three phase voltages on the PWM-CSC

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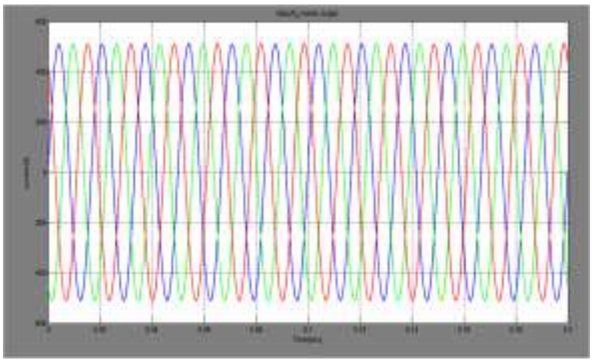


Fig. 12. Three phase currents on the PWM-CSC

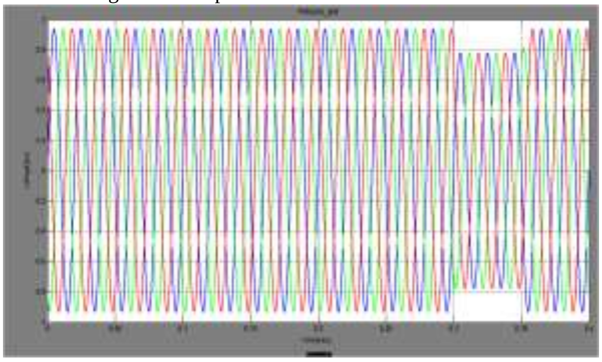


Fig.13. Response for three phase fault on grid output voltage waveform

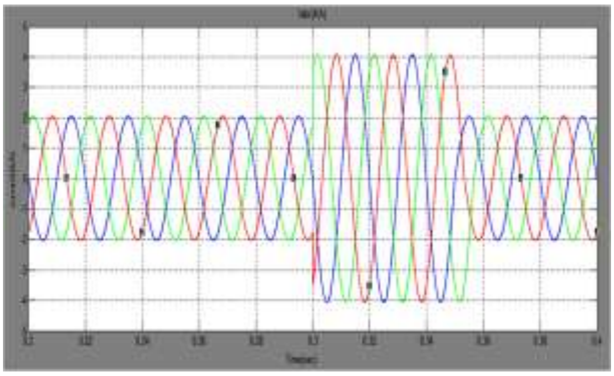
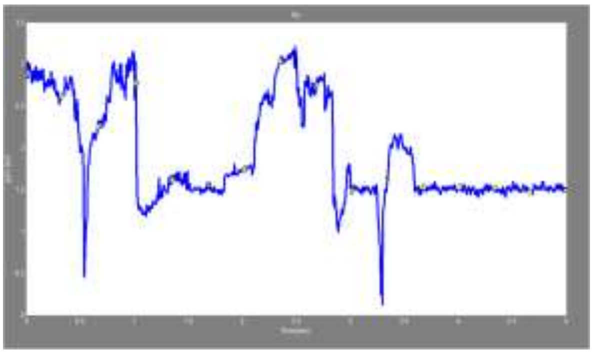


Fig. 14. Response for three phase fault on Grid output current waveform



(a)

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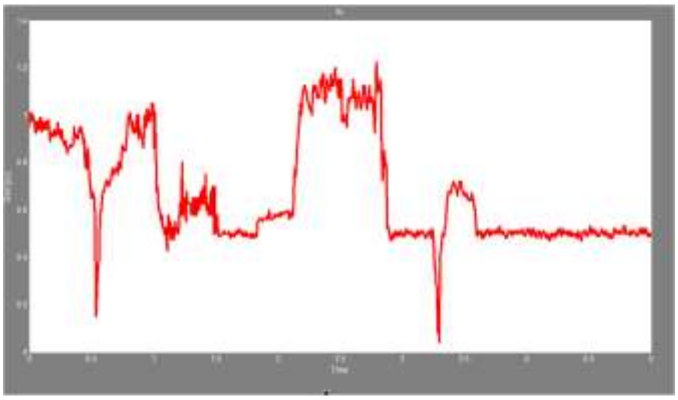

(b)

Fig. 15. Values of the adaptive controls(a)Kp and(b)Ki

V. CONCLUSIONS

Thus the PWM-CSC-based energy conversion system particularly designed for wind power applications was presented with a new controlling technology of adaptive control. If the desired performances cannot be achieved for the full range of possible parameter variations, adaptive control has to be considered in addition to a robust control design Both the control and the type of converter increase the flexibility of the wind turbine. They are able to operate in critical conditions such as short circuit and fast changes in wind velocity. The performance of the robust controller design will be improved by tuning of the controller using an adaptive control technique. Instantaneous Wind velocity measurements are not required & the reference model can enhance the transient behavior of the control after critical faults. For systems with time invariant behavior, the adaptive controller also behaves as a fixed controller. Therefore, it can be seen that the adaptive controller method can be used as a technique for self-tuning the controller based on the desired response.

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