International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 02 Issue: 06 | Sep-2015 www.irjet.net p-ISSN: 2395-0072

# An adjustable PI control technique for a wind energy conversion system based on a PWM-CSC and PMSG

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**Abstract -** ***Most of the studies on wind energy conversion systems are based on DFIG technology. Nevertheless, the proposed wind energy conversion system is a good alternate due to its adaptive control with hysteresis controller which can improve the efficiency and reliability. It has capable of controlling DC current according to the wind velocity independently of the DC voltage. Capacitive filters placed on the AC side, which are required for safe commutation can create resonances with the power grid. Maximum tracking point algorithm is modified in-terms of the DC current in the PWM-CSC. The adaptive PI control which is self- tuned based on a linear approximation of the power system calculated at each sample time. A model reference control is also included in order to reduce the post-fault voltages. Simulation results demonstrate the advantages of the proposed control.***

***Key Words:*** *Adaptive control, Hysteresis controller, pulse-width modulated current source converter, Permanent magnet synchronous generators, Reference model, etc.*

## 1. INTRODUCTION

Present wind power applications require flexible and efficient technologies that adapt to changes in load and generation. This is done by a combination of non-conventional energy sources and improved adaptive control strategies.

Most of the wind turbines use double fed induction generators in terms of the energy conversion system due to their high efficiency, improved controllability and educed rating of the converter [1]. Recently, other energy conversion systems and generator technologies have been proposed in [2]-[4]. In that, one of the most promising energy conversion system is based on permanent magnet synchronous generator. It has advantages in terms of power density and efficiency. In most cases, this type of generators are integration into the grid require a full rated AC/AC converter which is based on the voltage source converter technology. Another possible type is the pulse-width modulated current source converter (PWM-CSC) which has potentially more advantages for medium size wind turbines [5]. The capability of PWM-CSC is controlling the current on the DC side according to the wind velocity independently of the DC voltage. In this paper, this characteristic is exploited to create an adaptive control which does not require measure of the rotational speed. And also reliability, efficiency are improved by using a full bridge diode rectifier in the side of the machine.

Adaptive control is a key technology in electric energy systems and in smart-grids, because it allows the integration of wind energy resources as plug-and-play devices in electric power systems [6].

In order to auto adjust the controller parameters, the adaptive control that perform identification and control of dynamic systems can be highly-complex dynamic systems [8]. But the tuning of these controller parameters is a challenging task when the parameters of the controlled process either are poorly known or vary during normal operational conditions [9]. An adjustable PI control technique can be designed in order to achieve high-performance control systems [10]. However, the controlled process are almost time invariant during normal operation and in terms of reference tracking a fixed PI control have similar performance. When the process is time invariant, by using linear estimators it is possible to obtain a time varying linear approximation which can be used to self-tune the controller.

This paper proposes a new adjustable control strategy for a wind energy conversion system based on permanent magnet synchronous generator and pulse-width modulated current source converter with hysteresis controller. The proposed energy conversion system is a good alternate due to its high efficiency, reliability and reduction in Total Harmonic Distortion (THD). The control strategy uses an adaptive PI which is self-tuned based on a desired closed loop response and a linear approximation of the power system.

This paper is organized as follows: in section II the energy conversion system is presented and advantages of each component also described. Next, in section III the proposed adjustable control with hysteresis controller is deduced. After that, simulation results and explanation are presented. Finally, conclusions are presented in section V.

## 2. ENERGY CONVERSION SYSTEM

The proposed energy conversion system is based on PMSG. The main features of this type of machines which are relevant for wind power applications: reduced losses in the rotor; it requires lower maintenance and operating costs.

PMSGs allow smaller, flexible and lighter design as well as soft start and magnetization provided by permanent magnets. This characteristic implies an improvement in efficiency and effect the power electronic converter which does not require bidirectional power capability. Hence, a full bridge rectifier is enough for the AC/DC conversion.

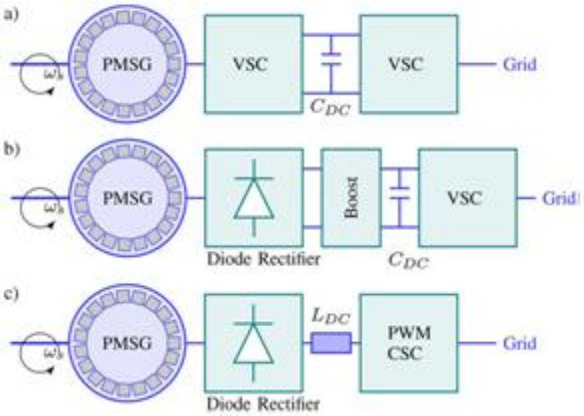

**Fig – 1:** Three possible configurations for PMSG integration: (a) back to back converter with VSCs, (b) diode-bridge rectifier and boost converter, and (c) proposed energy conversion system with PWM-CSC.

Usually, a permanent magnet synchronous generator requires a full rated converter which is back-to-back configuration with voltage source converters as shown in Fig. 1(a). This type of converter is efficient for integrating induction generators since it controls reactive power in the rectifier as well as in the inverter. However, a PMSG does not require reactive power and hence the rectifier can be replaced by a diode rectifier [11]. In order to maintain the DC voltage in a VSC must remain within certain limits. As a consequence of this, a DC/DC boost converter is required for controlling the power in the electric machine as depicted in Fig. 1(b). The use of a diode bridge rectifier in the conversion system improves the reliability and efficiency of the energy conversion system but the boost converter could have an opposite effect. Any power electronic converter based on forced commutations has two types of losses: switching losses and conduction losses. Switching losses are mainly related to the switching frequency while conduction losses are mainly depending on the collector current. Usually converters are design in such a way that switching and conduction losses are equal. A full bridge diode rectifier can be consider as a device with only conduction losses since switching losses occurs only once during each cycle.

A third option is to integrate the PMSG to the main grid through a diode rectifier and a PWM-CSC as given in Fig. 1(c). DC voltage variation is not a limitation on the PWM-CSC; hence the power can be directly controlled by the inverter. In addition, a PWM-CSC does not require electrolytic capacitors as the VSCs. Due to this type of electrolytic capacitors 30% of failures on AC converters are related and this also impacts the reliability of the systems [12].

Pulse-width modulated current source converter technology has been applied successfully in a wide range of applications such as motor drives [13], power quality conditioners [14] and HVDC transmission for offshore wind generation [15]-[17]. PWM-CSC is based on forced commutation and it is able to control the active and reactive power. In addition, it has capability to protect the system during the short circuit conditions [18].

The DC current is directly controlled by the converter. This feature is useful for low wind velocities when voltage in the machine is highly reduced. A PWM-CSC is able to adapt its voltage according to the wind velocity, while a VSC requires a constant voltage on DC side. This advantage of PWM-CSC improves the system efficiency.

A PWM-CSC requires semiconductor devices with reverse voltage blocking capability. So this can be added to a standard IGBT (Insulated Gate Bipolar Transistor) connected in series with a diode as shown in Fig. 2. Another alternate is the new type of semiconductor devices such as reverse blocking IGBTs or IGCTs (Insulated Gate Commutated Thyristors). The latter alternate is promising for PWM-CSCs [19].

The unity power factor is achieved by modulation itself. This can be done by using space vector modulation [5]. Another alternate for SVM is the Hysteresis controller.

In this paper SVM is replaced by hysteresis controller. Hysteresis control reduces the Total Harmonic Distortion (THD) which is presented in output voltage and also performance for weak grid is improved. Consequently the efficiency of the WECs is improved [24].

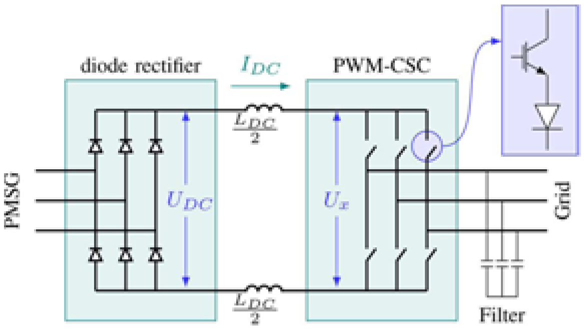

**Fig – 2:** pulse-width modulated current source converter

Nevertheless, PWM-CSC has some challenges related to the control of the converter [20]. The filter placed in the AC side can create resonances with the grid so that active damping techniques are required. However, these damping techniques are reducing the band width of the control [21]. In addition, the DC voltage must be control according to the wind velocity in order to improve the stability and efficiency.

## 3. PROPOSED ADAPTIVE CONTROL FOR PWM-CSC

A hierarchical control strategy is proposed for integrating of the wind turbine into the grid as shown in Fig. 4. First, maximum tracking point algorithm is modified in terms of the DC current in the PWM-CSC. Therefore, the reference for this current is modified dynamically according to the wind velocity. Next, an adaptive PI control is designed in order to track this reference current. And hysteresis control is proposed to improve the reliability of the system. Finally, a model reference control is included in order to reduce the over voltages resulting from a fault in the grid.

### *A. Maximum Tracking Point Algorithm*

The power generated by a wind turbine is given in (1):

$$P = \frac{1}{2}\rho . A . C_p(\lambda, \beta) . V^3 \qquad (1)$$

Maximum value of power transference is achieved by an optimal value of λ. The power generated is proportional to the cube of the wind velocity. The rotational speed ω must be proportional to the wind velocity and hence, power must be proportional to the cube of the rotational speed as given in (2):

$$P_{pu} = \frac{P(t)}{P_{nom}} = \left(\frac{\omega_s(t)}{\omega_{nom}}\right)^3 = \omega^3_{s(pu)} \qquad (2)$$

The generated power is given by $U_{DC}.I_{DC}$ (PMSG losses are ignored). As a result, the optimal $I_{DC}$ to achieve maximum tracking is given by (3):

$$I_{DC}(t) = G . (U_{DC}(t))^2 \qquad (3)$$

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

$$G \approx \frac{P_{nom}}{U^2_{DC(nom)}} \qquad (4)$$

The power delivered by the converter is given by (5):

$$P_x(t) = Real\{(m(t).e^{j\theta(t)})I_{DC}(t)(U_y(t).e^{j\theta(t)})^*\} \quad .... \quad (5)$$

Where, $\theta$ is the angle of the output current. This angle must equal to the angle of the grid voltage to achieve a unity power factor.

The output power beyond the capacitive filter is approximately equal to the $P_x$. Usually, the control in the current source converters is made in two stages, one controlling the active power and the other one controlling the voltage in the AC side. This approche directly controls both the active and reactive power is maintained by the modulation itself. Therefore, the possible resonances on the controls are reduced. The resulting nonlinear time varying system requires an adaptive control as will be demonstrated in the next subsection.

### *B. Adaptive Control*

In any control strategy, the adaptive control which uses parameter esimation of the plant in real time by using recursive identification. The adaptive controller to be designed is based on the certainity equivalence princple: design the controller as long as plant parameters are known. However, these plant parmeters are unkown at time $t_k$, they are replaced by an estimated online identifier given in [22].

An adaptive PI control is designed in such a way that where the plant parameters are estimated by an online identifier, as shown in Fig. 4. It is easy to implement, since for the controlled plant, only the output signal is needed for feedback.

In continuous time, a PI controller can be defined as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \qquad (6)$$

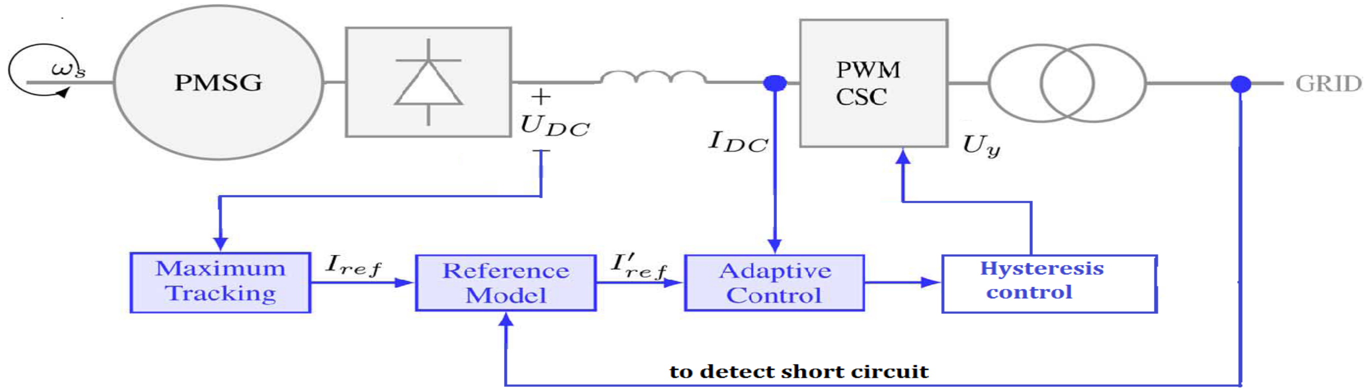

**Fig – 3:** Proposed hierarchical strategy for adaptive control of the energy conversion system based on a pulse-width modulated current source converter

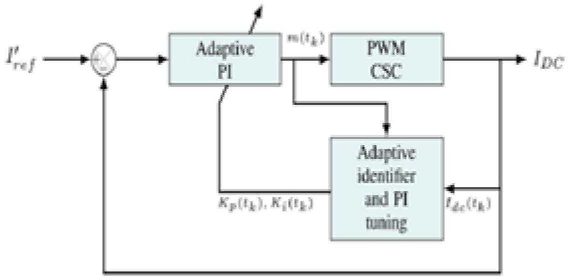

**Fig – 4:** Adaptive control and identifier

In discrete time, the PI controller can be defined as

$$e_i(t_k) = e_i(t_{k-1}) + e(t_k) \tag{7}$$

$$u(t_k) = K_p e(t_k) + K_i h e_i(t_k) \tag{8}$$

Obtaining the following expression for the PI controller in discrete time

$$u(t_k) = \frac{c_1 + c_2 q^{-1}}{1 - q^{-1}} e(t_k) \tag{9}$$

If defining desired closed loop poles, given by

$$P_d(z) = (1 - \alpha_1 z^{-1})(1 - \alpha_2 z^{-2}) \tag{10}$$

Where $\alpha_1$ and $\alpha_2$ are the discrete time roots, which are related to the continuous time roots $s_1$ and $s_2$ by using

$$\alpha_1 = e^{s_1 h} \tag{11}$$

$$\alpha_2 = e^{s_2 h} \tag{12}$$

Finally, the controller parameters $K_p$ and $K_i$ can be calculated by

$$K_p(t_k) = -c_2(t_k) \tag{13}$$

$$K_i(t_k) = \frac{c_1(t_k) + c_2(t_k)}{h} \tag{14}$$

Therefore, the resultant controller is an adaptive PI control for each $t_k$. The behavior of the controller can be determined by the selection of the desired closed loop poles of (10) and the sample time $h$, according to (11).

### *C. Model Reference Adaptive Control*

During short circuit, reference current is modified in order to improve the short circuit behavior of the converter. A slightly different current $I_{ref}$ in which the desired output is generated by a linear reference model is proposed. The order of the reference model can be selected as less than or equal to the order of the process. In this work, a zero order model is used in pre-fault($I'_{ref} = I_{ref}$), no control during the fault($I'_{ref} = I_{DC}$) and a first order after the fault as follows:

$$I'_{ref} = H_m(z) I_{ref} \tag{15}$$

$$H_m(z) = \frac{(1-\rho_0)z^{-1}}{1-\rho_0 z^{-1}} \tag{16}$$

Where $\rho_0$ must be selected as a stable root, where it is known that the reference model must be selected as a stable model with unitary gain. However, it is clear 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 voltage in the input of the PWM-CSC.

### *D. Hysteresis Control*

Hysteresis control is proposed for replacing the space vector modulation in the hierarchical strategy for adaptive control of the energy conversion system as shown in Fig. 3. Some significant advantages of hysteresis controller are as follows: switching behavior of the inverter can be taken directly into the account; it is possible to implement the hardware in simple manner; fast dynamic response and robustness to load parameters.

In this paper, hysteresis control is proposed in order to improve the dynamic response and reduce the total harmonic distortion presented in the system.

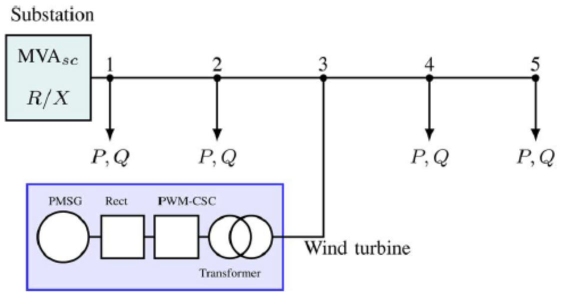

**Fig – 5:** Simulated primary feeder with the proposed energy conversion system

**Table 1:** PARAMETERS OF THE SYSTEM

| Parameter | Value | Unit | Component |
|---|---|---|---|
| Nominal Power | 2 | MVA | PMSG |
| Nominal Voltage | 690 | V | |
| Nominal rotational speed | 2π34 | rad/s | |
| Stator phase resistance | 0.05 | pu | |
| Armature impedance | 0.80 | pu | |
| Flux | 1.50 | pu | |
| Nominal wind velocity | 12 | m/s | Turbine |
| Nominal Power | 2 | MW | |
| Inertia constant | 1.27 | s | |
| Nominal DC current | 2 | KA | PWM-CSC |
| Switching Frequency | 1 | KHz | |
| Nominal voltage | 13.2 | KV | Grid |
| Three-phase short circuit power | 100 | MW | |
| Cut-off frequency | 200 | Hz | AC filter |
| X/R ratio | 7 | | |
| Frequency | 60 | Hz | |
| $\alpha_1$ | 0.8 | | Control |
| $\alpha_2$ | 0.8 | | |
| $\rho_0$ | 0.99 | | |
| h | 1 | ms | |

## 4. RESULTS

A detailed switching model of the proposed energy conversion system based on pulse-width modulated current source converter with hysteresis controller was simulated by using Matlab-Simulink. The system consists of a 13.2 KV distribution feeder with a 2 MW wind turbine as shown in Fig. 5. Parameters of the wind energy conversion system are shown in Table 1.

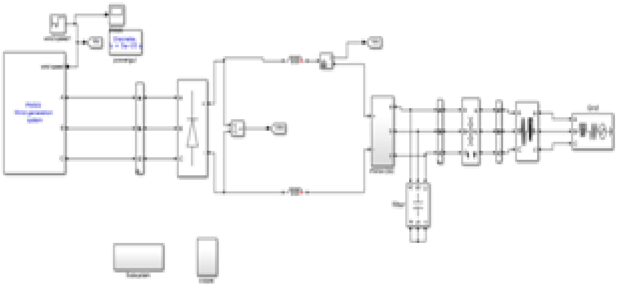

**Fig – 6:** Simulation block for proposed wind energy conversion system

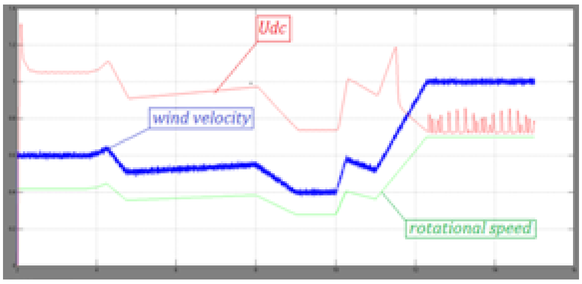

Fig -7: Wind velocity, rotational speed and DC voltage

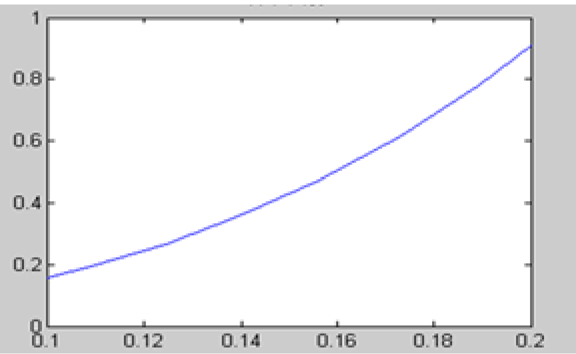

Fig. 8 Voltage $U_{DC}$ versus rotational speed

The discrete time roots were selected in order to achieve steady state in 20 ms. On the other hand, the reference model for the short circuit condition was calculated for 400 ms.

Wind velocity for 15-s simulation is illustrated in Fig. 6. Base wind velocity is 12 m/s. Wind velocity for profile was created by using a detailed model which considers stochastic behavior [23]. A gust is simulated in the proposed control in order to demonstrate the maximum power tracking capability. DC voltage, wind velocity and rotational speed are plotted in Fig. 7. Rotational speed and DC voltages are proportional as expected. Fig. 8 shows the DC voltage with respect to the rotational speed for the aforementioned simulation. The linear approximation is more accurate for low wind velocities and at high velocities, the generated power increases the current and hence, the voltage drop on the inductances influences the generated voltage. Nevertheless, the linear approximation is accurate from a practical point of view and maximum tracking is achieved as shown in Fig. 9. Generated power and wind velocity are shown in this figure. An almost perfect tracking characteristic is achieved in DC current as shown in Fig. 10.

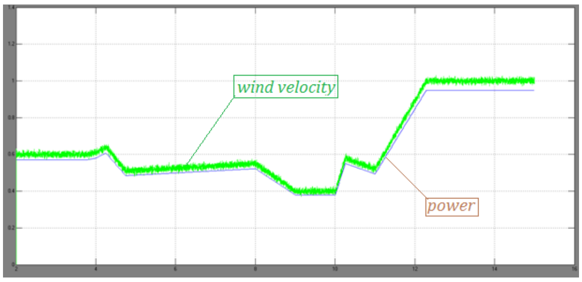

Fig. 9 Generated power in the point of common coupling

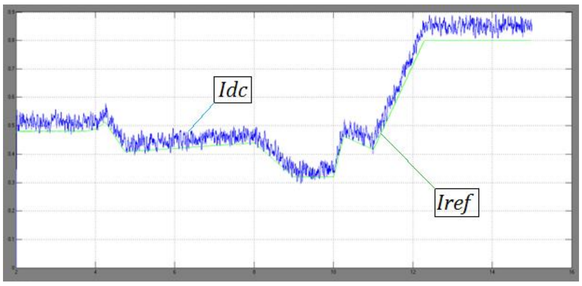

**Fig -10:** DC current and reference current

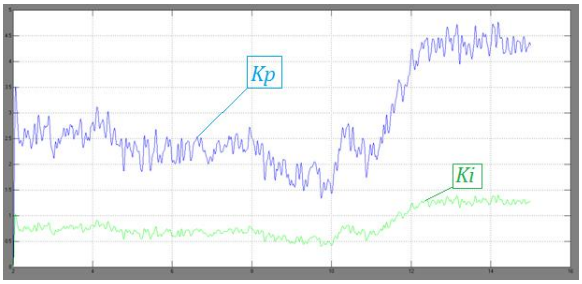

**Fig -11:** Values of the adaptive controls $K_p$ and $K_i$

The control strategy changes dynamically according to the wind conditions as shown in Fig. 11. The performance could be similar at least at nominal velocity for a time invariant PI control. In that case, the proposed algorithm can be used as a tuning technique. Three-phase voltages and currents in the PWM-CSC are shown in the Fig. 12.

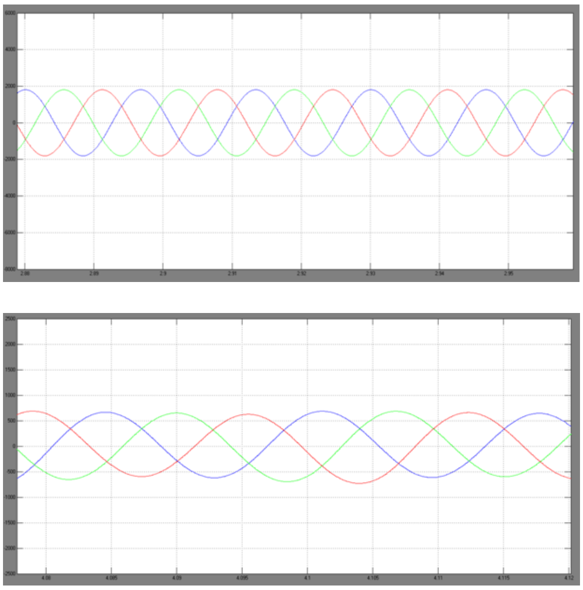

**Fig -12:** Three-phase voltages and currents on the PWM-CSC

The harmonic disturbances are presented in three-phase voltages due to the commutation process. They are attenuated by the transformer and hence, the voltage in the point of common coupling is completely sinusoidal. By increasing the switching frequency smoother wave form can be achieved. This can be done by a hysteresis controller which perform the smoother operation and reduce the total harmonic distortion.

Transient behavior of the proposed control was also tested in the same distribution feeder. Wind velocity was maintained constant in 12 m/s. A three-phase short circuit was simulated at Node 3 in t=3 s (see Fig. 6). Results are shown in Fig. 13. The grid voltage is dropped to almost zero [Fig. 13(a)]. Current $I_{DC}$ increased due to drop on the grid voltage in Node 3. The converter still worked in this condition maintaining the unity power factor. The reference model enter into operation by maintaining $I'_{ref} = I_{DC}$. This allows for energy storage in the inductance during a fault. The reference current smoothly changes depend on the wind velocity.

The parameters of the control decreases at Node 3 as shown in Fig. 13(c) and these are return to their normal values after the fault is cleared. Due to the introduction of the reference model the voltage and current values after fault are within maximum limits.

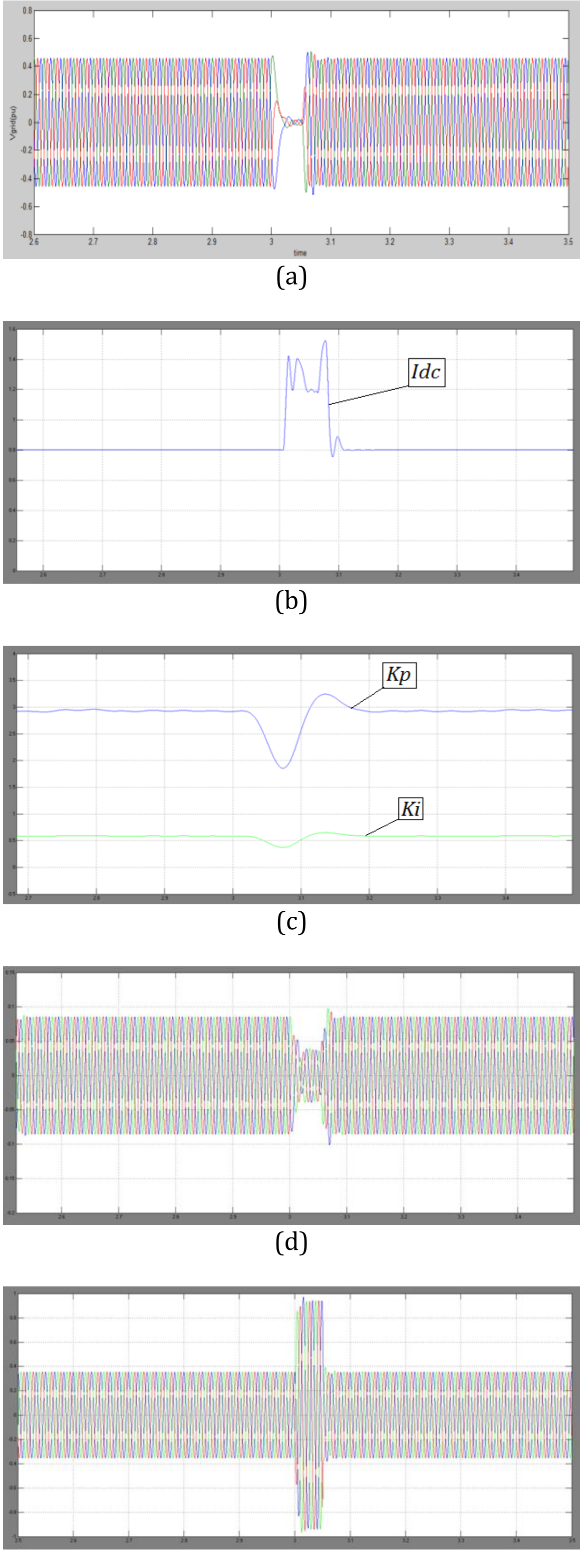

**Fig -13:** Response for a three-phase fault in the grid. (a) Grid voltages.(b) DC current.(c) Control variables.(d) Voltages at the primary of the transformer.(e) Output currents.

The THD values are reduced by using hysteresis control and compared as shown in Table 2.

**Table 2:** THD values

| Method | %THD for Voltage | %THD for Current |
|---|---|---|
| SVM (existing)[20] | 19.57 | 44.07 |
| Hysteresis control (proposed)[24] | 14.95 | 42.03 |

## 5. CONCLUSIONS

An adjustable control with hysteresis control for a PWM-CSC based wind energy conversion system was presented particularly for wind power applications. Hysteresis control is used to reduce the total harmonic distortion present in the system and hence the efficiency was improved. Both the control and type of converter increase the flexibility of the converter. They are able to operate in critical fault conditions and sudden changes in wind velocity. No need to measure the rotational speed. A reference model can be used to improve the transient behavior of the control under severe faults. The adaptive controller behaves as a fixed controller for time invariant systems. Therefore, it can be observe that the adaptive controller technique can be used for self tuning the controller based on the desired response.

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