A Fuzzy Logic Controller for a Wind Energy Conversion System Based on PWM-CSC and PMSG

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Abstract: This paper proposes a fuzzy logic controller for wind energy conversion system based on permanent magnet synchronous generator and pulse width modulated current source converter. Integration in the grid for this type of generator requires a converter. Here type of converter is pulse width modulated current source converter (PWM-CSC). Power generated by PMSG is modified according to the wind velocity and load profile by the converter. The fuzzy logic controller which is based on human expertise knowledge is employed to overcome all the setbacks witnessed in all the other controllers. Fuzzy logic has the features of simple concept, easy implementation, and computationally efficient. The function of FLC is to track the generator speed with the reference speed for maximum power extraction at variable speeds.

Index Terms- Fuzzy logic control, permanent magnet synchronous generator, pulse-width modulated current source converter, reference model, wind energy.

NOMENCLATURE

V	Wind velocity.
A	Area swept by the blades.
ρ	Air density.
λ	Tip ratio.
B	Pitch angle.
Cp	Coefficient of power.
w_s	Rotational speed.
R_s	Stator phase resistance of the machine.
L_s	Armature inductance.
L_{DC}	Inductance in the PWM-CSC.
U_{DC}	Voltage in the output of the diode rectifier

I. INTRODUCTION

The increasing number of renewable energy sources and distributed generators requires new strategies for the operation and management of the electricity grid in order to maintain or even to improve the power-supply reliability and quality.

In terms of the energy conversion system, there are different wind turbine configurations for extracting energy from the wind including using synchronous or asynchronous machines. Most of the wind turbines for on-land emplacements use double fed induction generators due to their economic advantages (i.e., high efficiency, improved controllability and reduced rating of the converter [1]). Nevertheless, other energy conversion systems and generator technologies have been proposed recently [1]–[5]. One of the most promising of them is the permanent magnet synchronous generator (PMSG) which has clear advantages in terms of efficiency and power density. A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. Synchronous generators are the majority source of commercial electrical energy. The permanent-magnet synchronous generator (PMSG), which is less noisy, high efficiency and has a long life span, has becomes one of the most important types of equipment in wind turbine systems.

Integration into the grid of this type of generators requires a full rated AC/AC converter. Here PWM-CSC is used as converter which has potentially more advantages for medium size wind turbines [6]. It is capable of controlling the DC current according to the wind velocity independently of the DC voltage. It also could be shown that discontinuous PWM for the VSC could be modified to attain optimal switching patterns for the CSC regarding switching losses on the one hand and harmonic generation on the other hand up to a certain extend [2], [3].

PWM CSCs provide a simple topology solution and excellent grid integration performance, such as sinusoidal current and fully controlled power factor. Current-source converter not only controls real and reactive power flow in the network, but also regulates the dc link current.

FLC introduced to regulate the rotational speed to force the PMSG to work around its maximum power point in speeds below rated speeds and to produce the rated power in wind speed higher than the rated wind speed of the WT. The input to FLC is two real time measurements which are the change of output power and rotational speed between two consequent iterations. The output from FLC is the required change in the rotational speed.

II. ENERGY CONVERSION SYSTEM

In energy conversion system, the gearless direct drive (DD) and WTs have been used with small and medium size WTs employing permanent magnet synchronous generator (PMSG) with higher numbers of poles to eliminate the need for gearbox which can be translated to higher efficiency. PMSG appears more and more attractive, because of the advantages of permanent magnet, PM machines over electrically excited machines such as its higher efficiency, higher energy yield, and no additional power supply for the magnet field excitation, and higher reliability due to the absence of mechanical components such as slip rings. In addition, the performance of PM materials is improving, and the cost is decreasing in recent years. Therefore, these advantages make direct-drive PM wind turbine generator systems more attractive in application of small and medium-scale wind turbines.

Pulse-width modulated current source converter technology has been applied successfully in a wide range of applications such as motor drives [9], power quality conditioners [10] and HVDC transmission for offshore wind generation [11]-[13]. 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 [14].

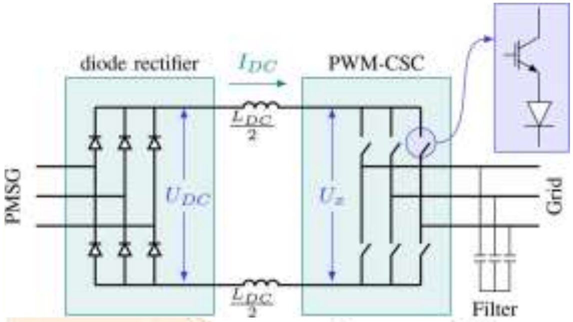


Figure 1: Pulse-width modulated current source converter.

A. MAXIMUN TRCKING POINT

Wind turbine converts the wind power to a mechanical power. This mechanical power generated by wind turbine at the shaft of the generator can be expressed as:

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

Where ρ is the air density (typically 1.225 kg/m3), β is the pitch angle (in degree), A is the area swept by the rotor blades; u is the wind speed (in m/s), and $C_p(\lambda, \beta)$ is the wind turbine power coefficient (dimensionless).

The turbine power coefficient, $C_p(\lambda, \beta)$, describes the power extraction efficiency of the wind turbine and is defined as the ratio between the mechanical power available at the turbine shaft and the power available in wind. A generic equation is used to model $C_p(\lambda, \beta)$.

Maximum power transference is achieved by an optimal value of λ. Consequently 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):

$$P_{pu} = \frac{P(t)}{P_{nom}} = \left(\frac{w_s(t)}{w_{nom}}\right)3 = w^3(pu) \qquad (2)$$

On the other hand, the PMSG is modeled on the rotor reference Frame (dq) as follows:

$$u_{s(d)} = R_s.i_{s(d)} + L_s\frac{d}{dt}i_{s(d)} - L_s.w_s.i_{s(q)} \qquad (3)$$

$$u_{s(q)} = R_s.i_{s(q)} + L_s\frac{d}{dt}i_{s(q)} - L_s.w_s.i_{s(d)} + \psi_m.w_s \qquad (4)$$

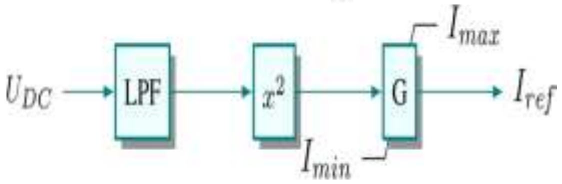


Figure 2: Reference for using a maximum tracking point algorithm

The voltageU_{DC} on the diode rectifier (see Fig. 2) is proportional to the voltage in the terminals of the machine which in turn is given by (5) where ϕ is a proportional constant:

$$U_{DC(pu)} = \phi.w_s. \qquad (5)$$

This expression was obtained by replacing (2) in the model of the PMSG in stationary state and ignoring the voltage drop in the inductance.. A speed sensor is not required when using this expression since the voltageU_{DC} is measured. The generated power is given by$\mathrm{U}_{DC}.\mathrm{I}_{DC}$ (PMSG losses are ignored). As a result, the optimal $\mathrm{I}_{DC}$to achieve maximum tracking is given by (6):

$$\mathrm{I}_{DC}(t) = G.(\mathrm{U}_{DC}(t))2 \qquad (6)$$

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

$$G = \left(\frac{P_{nom}}{U_{DC}{}^{2}{}_{(nom)}}\right) \quad (7)$$

This equation establishes a set point for current as given in Fig. 2. A low pass digital filter (LPF) is required to smooth voltageU_{DC} . The cut-off frequency is set below commutation frequency. On the other hand, the dynamics $I_{DC}$of depends on the inductanceL_{DC} as follows:

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

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

$$P(t) = \frac{L_{DC}}{2} \frac{d}{dt} I^2{}_{DC} + P_u(t) \quad (9)$$

Where, $P_x$is the power delivered by the converter which in turn depends on the modulation index m as follows:

$$\mathrm{P}_x(t) = Real\{(m(t).e^{j\theta(t)})\mathrm{I}_{DC}(t)(\mathrm{U}_y(t).e^{j\theta(t)})\} \quad (10)$$

Where, θ is the angle of the output current. This angle must be equal to the angle of the grid voltage in order to achieve a unity power factor. A phase locked loop is required. Therefore, the only control variable is as given in (11):

$$\mathrm{P}_x(t) = \boldsymbol{m(t)}.I_{DC}(t).I_{DC}(t) \quad (11)$$

III. FUZZY LOGIC CONTROLLER FOR MPPT

A hierarchical control is proposed for integration of the wind turbine into the grid .First, the 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.

At certain wind speed, the power is maximized at a certain ω called optimum rotational speed ω. This speed corresponds to optimum tip speed ratio, λ. So, to extract maximum power at variable wind speed, the turbine should always operate at λ. This occurs by controlling the rotational speed of the turbine. Controlling of the turbine to operate at optimum rotational speed can be done using the FLC. Each wind turbine has one value of λ at variable speed but ω changes from a certain wind speed to another. The relation between ω and wind speed, V, for constants R and λ can be obtained as follows:

$$\omega = \frac{\lambda}{R}\mathrm{V} \quad (12)$$

The relation between the optimum rotational speed and wind speed is linear. FLC is used to search the rotational speed reference which tracks the maximum power point at variable wind speeds. The block diagram of FLC is shown in Fig. 3. Two variables are used as input to FLC (ω and P) and the output is (Δω*). Membership functions are shown in Fig. 4.Triangular symmetrical membership functions are suitable for the input and output, which give more sensitivity especially as variables approach to zero value. FLC does not require any detailed mathematical model of the system and its operation is governed simply by a set of rules. The principle of the FLC is to perturb the reference speed and to observe the corresponding change of power. If the output power increases with the last speed increment, the searching process continues in the same direction. On the other hand, if the speed increment reduces the output power, the direction of the searching is reversed. The FLC is efficient to track the maximum power point, especially in case of frequently changing wind conditions.

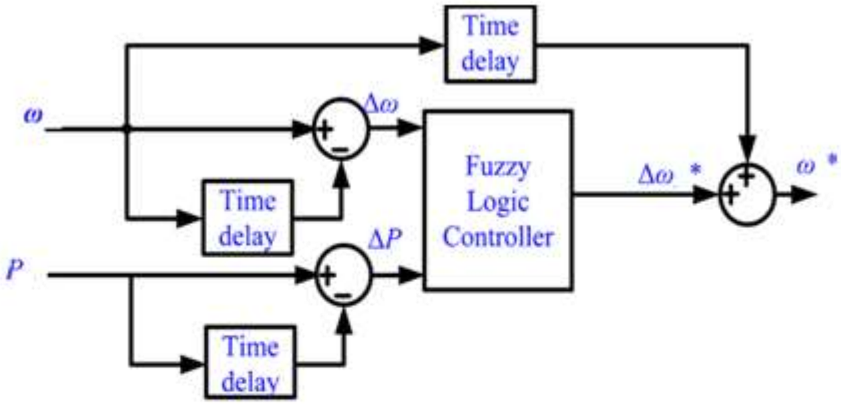
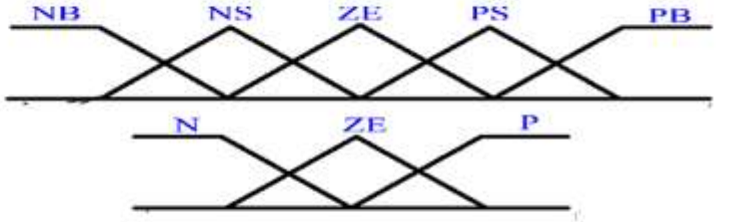
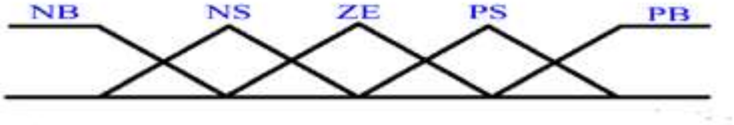


Figure 3: Input and output of fuzzy controller



Input membership functions of ΔP and $\Delta\omega$ respectively



Output membership functions

Figure 4: Membership functions of FLC

The input and output membership functions have been shown in Fig. 4. Δω is varied from -1 rad/s to 1 rad/s. The control rule for input and output variables are listed in Table I. The membership definitions are used as follows: N (negative), NB (negative big), NS (negative small), ZE (zero), P (positive), PS (positive small), and PB (positive big).

Table I: Rules for FLC

ΔP/Δω	NB	NS	ZE	PS	PB
N	PB	PS	ZE	NS	NB
ZE	NM	NS	ZE	PS	PM
P	NB	NS	ZE	PM	PB

IV. PROPOSED WORK

Simulation results shows boost converter operation with fuzzy based control. MATLAB simulation was utilized to perform the simulation for the analysis. 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 Figure 6.

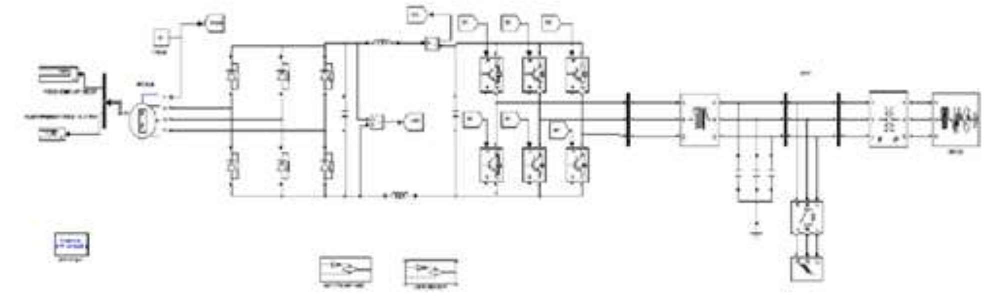


Figure 5: Proposed simulation circuit for fuzzy logic controller of the energy conversion system based on PMSG and PWM-CSC.

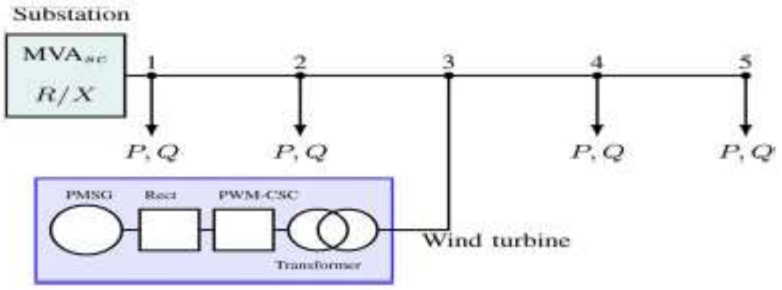


Figure 6: Simulated primary feeder with the proposed energy conversion system

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 [8]. 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 of view and maximum tracking is achieved. High inertia of the set turbine-generator produces a delay in the rotational-speed tracking capability but also a smoothing effect. This is expected in almost all type of controls for wind energy. An almost perfect tracking characteristic is achieved in I_{DC}as illustrated in Fig.7. Three-phase voltages and currents in the PWM-CSC are shown in Fig. 8. Small harmonic distortions are present 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. A smoother waveform can be achieved by increasing the switching frequency at the expense of higher switching losses. 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 at Node 3 was simulated in (see Fig. 6). Results are shown in Fig. 9. The voltage on the grid dropped to almost zero [Fig. 9(a)]. Current increased due to the 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. This allows for energy storage in the inductance during a fault. The reference for changes smoothly since it depends on the wind velocity. The modulation index increases up to the point of over-modulation. Consequently, the parameters of the control decreases. These parameters return to their normal values after the fault is cleared. Notice that the voltages and currents after the fault are within the maximum limits due to the introduction of the reference model.

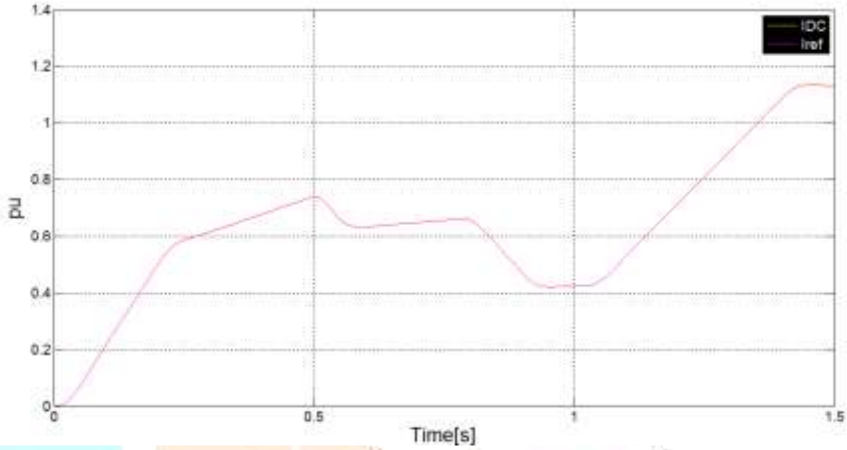


Figure 7: DC currentI_{DC} and reference I_{ref} .

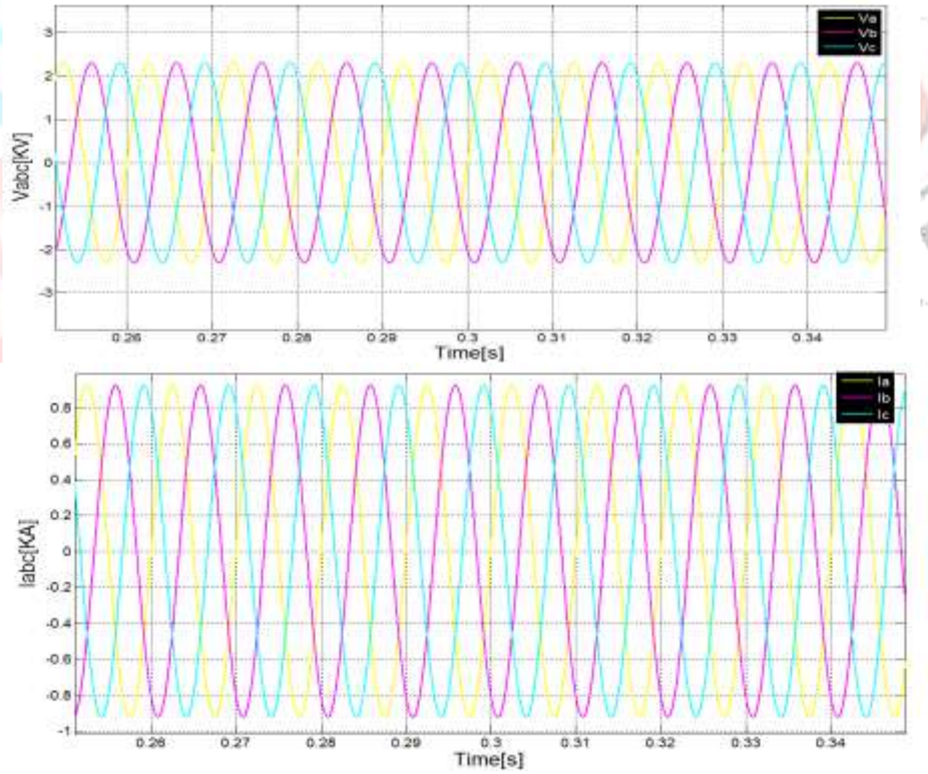


Figure 8: Three-phase voltages and currents on the PWM-CSC.

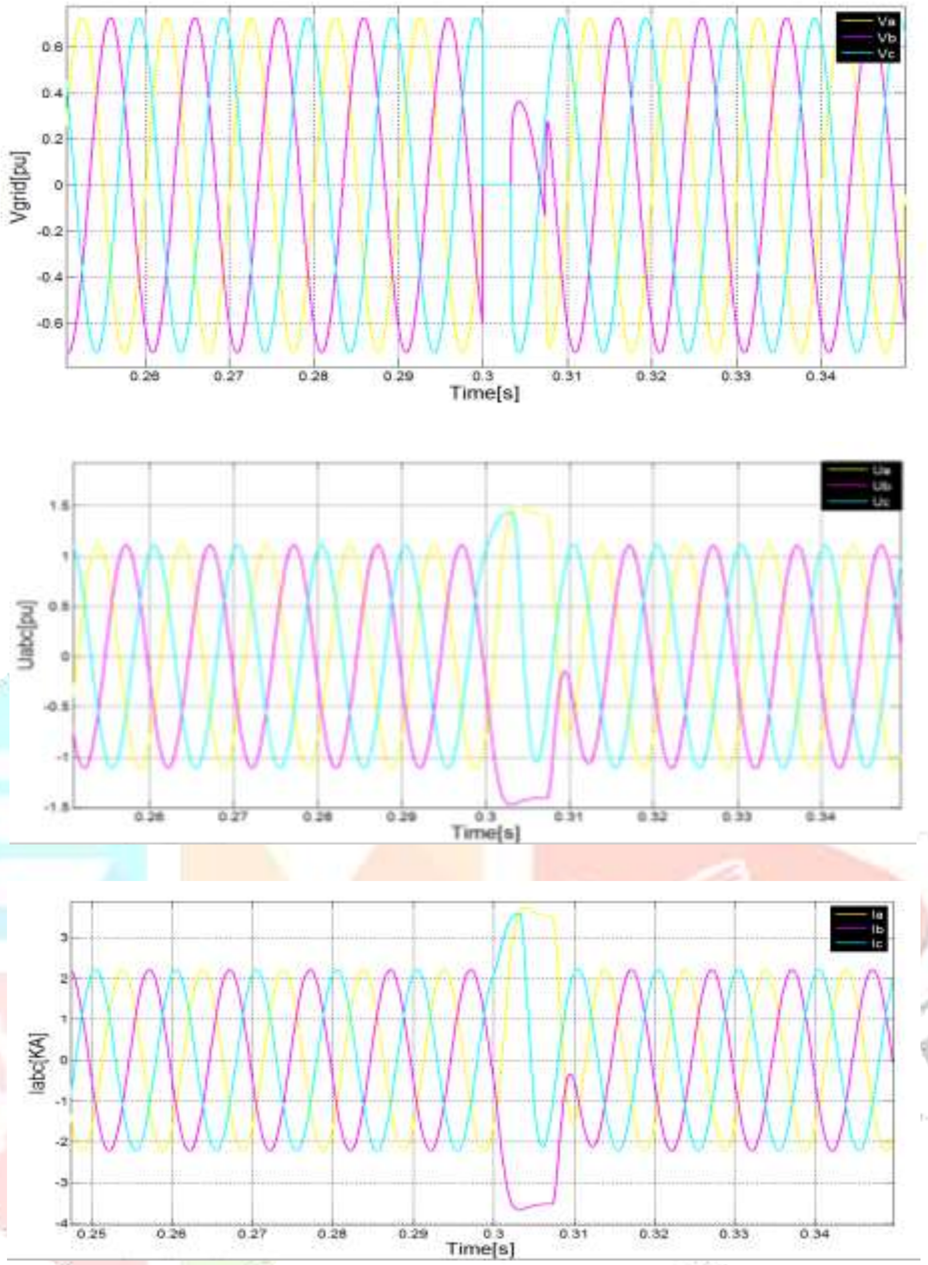


Figure 9: Response for a three-phase fault in the grid. (a) Grid voltages (d) Voltages at the primary of the transformer. (e) Output currents.

V. CONCLUSION

From above the discussion fuzzy logic control for a PWM-CSC-based energy conversion system has been implemented by using simulation technique for wind power conversion system and tested successfully. So we can conclude that the efficient working model of wind conversion system can be predicted by using Fuzzy Logic controller with MATLAB software. It will surely help us to develop various energy harvesting systems using simulations. Both the control and the type of converter increase the flexibility of the wind turbine. This design allows wind turbine to operate continuously varying conditions such as short circuit and fast changes in wind velocity. Measurements of wind velocity or rotational speed are not required. Fuzzy logic controller behaves like a fixed controller for time invariant systems. Maximum power from wind is tracked by the controller through controlling the rotational speed of the turbine using fuzzy logic controller. A simulation result shows how FLC is superior to conventional controllers.

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