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Mitigation of Power Quality problems by UPQC for Renewable Energy Resources using Fuzzy Logic Technique

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ABSTRACT
The wind energy conversion system Wind Farms (WF) are employ squirrel cage induction generator (SCIG). The injection of wind power into an electric grid causes the power quality problems such as variation of voltage, flicker, harmonics etc, and these are measured according to national/international guidelines. To solve these problems Custom Power Devices (CUPS) are used. This paper has proposed a compensation strategy based on a particular cups device for Unified Power Quality Compensator (UPQC) with an application of PI and Fuzzy Logic Controllers. The proposed strategy controls both active and reactive power in the converters of UPQC. This paper presents the comparison between without UPQC, UPQC with PI controller and UPQC with Fuzzy Logic Controller. By using MATLAB/SIMULINK software the control strategies are designed. The simulation results are shown for comparison of different control strategies and by performing FFT analysis Total Harmonic Distortions (THD) are calculated.
Keywords — Fuzzy Logic Controller, UPQC, voltage fluctuation, Wind Energy, Total Harmonic Distortion (THD)

I. INTRODUCTION

The integration of wind energy into existing power system presents technical challenges and that requires consideration of voltage regulation, stability and power quality. The power quality issues can be viewed with respect to wind farms are generation, transmission and distribution network such as voltage sag or swell, flickers, harmonics etc. [1]

Because of the random nature of wind resources, the WF generates fluctuating electric power. These fluctuations have a negative impact on stability and power quality in electric power systems [3].

Moreover, in utilization of wind resources, turbines employing squirrel cage induction generators (SCIG) have been used because it is simple, reliable, requires less maintenance and cost effective. The operation of SCIG demands reactive power, usually provided from the mains and/or by local generation in capacitor banks [4], [5]. In the event that changes occur in its mechanical speed, i.e. due to wind disturbances, so the WF active (reactive) power injected (demanded) into the power grid, leading to variations of WF terminal voltage.

In order to reduce the voltage fluctuations that may cause "flicker" and to improve the WF terminal voltage regulation, several solutions have been posed.

The use of active compensators allows great flexibility in: a) controlling the power flow in transmission systems using Flexible AC Transmission System (FACTS) devices, and b) enhancing the power quality in distribution systems employing Custom Power System (CUPS) devices [6], [9]. The use of these active compensators to improve integration of wind energy in weak grids is the approach adopted in this work.

In this paper we propose a compensation strategy using one of the Custom Power Devices CUPS devices known as UPQC for the three cases: 1) without UPQC 2) UPQC with PI controller and 3) UPQC with Fuzzy Logic Controller.

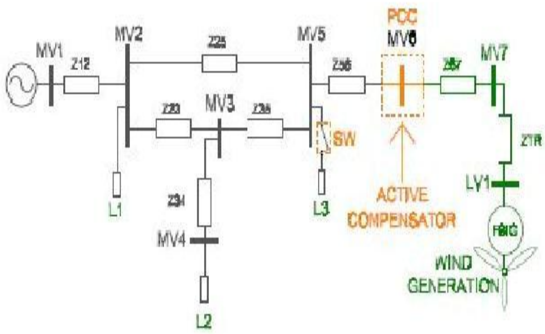

Fig.1 Study Case Power System

This system is taken from a real case [7]. The UPQC is controlled to regulate the WF terminal voltage, and to mitigate voltage fluctuations at the point of common coupling (PCC), caused by system load changes and pulsating WF generated power, respectively.

II. MODELLING OF CASE STUDY

2.1 System description

The chosen study case for this investigation is shown in Fig. 1 and is based on an operating wind farm. The wind farm consists of 36 x 600kW fixed speed stall regulated wind turbines. Each wind turbine is connected to the wind farm power collection network by a 630kVA, 0.69/33 kV transformers. Power factor correction capacitors (PFC) of 175kVAr are connected at the terminals of each wind turbine generator. The wind farm is connected to the 33kV network.

The ratio between short circuit power and rated WF power, give us an idea of the "connection weakness". Thus considering that the value of short circuit power in MV6 is SSC ≃ 120MVA, this ratio can be calculated:

$$R = \frac{S_{SC}}{P_{WF}} \cong 5.5$$

Values of $r < 20$ are considered as a "weak grid" connection.

2.2. Wind Energy Generating System

In this configuration, wind generations are based on constant speed topologies with pitch control turbine. The induction generator is used in the proposed scheme because of its simplicity, it does not require a separate field circuit, it can accept constant and variable loads, and has natural protection against short circuit. The available power of wind energy system is presented as under in Eq. 1

$$P_{wind} = \frac{1}{2}\rho A V_{wind}^3 \quad (1)$$

Where ρ (kg/m) is the air density and A (m^2) is the area swept out by turbine blade, V wind is the wind speed in meters/second.

It is not possible to extract all kinetic energy of wind, thus it extract a fraction of power in wind, called power coefficient C_p of the wind turbine, and is given in Eq. 2

$$P_{mech} = C_p P_{wind} \quad (2)$$

Where C_p is the power coefficient, depends on type and operating condition of wind turbine. This coefficient can be express as a function of tip speed ratio λ and pitch angle θ. The mechanical power produce by wind turbine is given in Eq. 3

$$P_{mech} = \frac{1}{2}\rho\pi R^2 V_{wind}^3 C_p \quad (3)$$

Where R is the radius of the blade (m).For the considered turbines (600kW) the values are R = 31.2m, ρ = 1.225 kg/m3 and C_p calculation is taken from [8]. Then, a complete model of the WF is obtained by turbine aggregation; this implies that the whole WF can be modeled by only one equivalent wind turbine, whose power is the arithmetic sum of the power generated by each turbine according to the following equation:

$$P_t = \sum P_i \quad (4)$$

$i = 1, 2…..36.$

2.3 Fixed Speed Induction Generator

The stator winding is connected directly to the grid and the rotor is driven by wind turbine and is transmitted to the grid by the stator winding. The pitch angle is controlled to limit the generator output power to its nominal value for high wind speeds. The reactive power is absorbed by the induction generator is provided by grid.

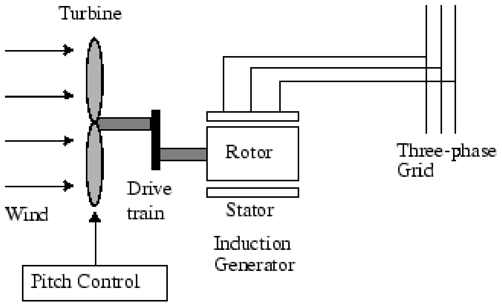

Fig.2 Connection of Wind Turbine to the Induction Generator

III. UPQC CONTROL STATEGY

Fig.3 shows the basic outline of this compensator. The operation is based on the generation of three phase voltages, using electronic converters either voltage source type (VSI–Voltage Source Inverter) or current source type (CSI– Current Source Inverter). VSI converter are preferred because of lower DC link losses and faster response in the system than CSI .The shunt converter of UPQC is responsible for injecting current at PCC, while the series converter generates voltages between PCC and U1, as illustrated in the phasor diagram of Fig.4

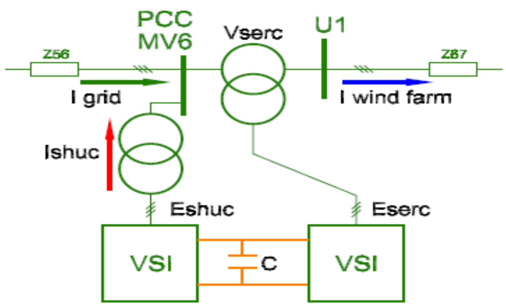

Fig.3 Block diagram of UPQC

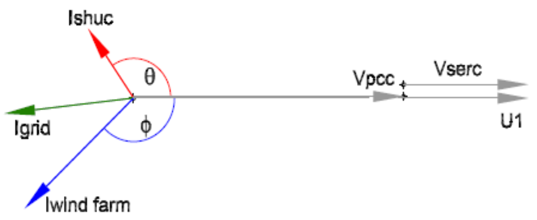

Fig.4 Phasor diagram of UPQC

An important feature of this compensator is the operation of both VSI converters (series and shunt) sharing the same DC–bus, which enables the active power exchange between them. We have developed a simulation model for the UPQC based on the ideas taken from [10].

The control of the UPQC, will be implemented in a rotating frame dq0 using Park's transformation (Eq.5-6)

$$T = \frac{2}{3}\begin{bmatrix} \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} f_d \\ f_q \\ f_o \end{bmatrix} = T.\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (6)$$

Where $f_{i=a,b,c}$ represents either phase voltage or currents, or $f_{i=d,q,o}$ represents those magnitudes transformed to the d,q,o space. According to the adopted control scheme, these two parts of UPQC have different functions as follows:

3.1 Static Series Compensator

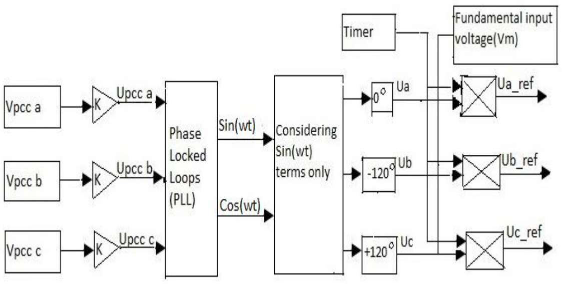

Fig.5 Extraction of Unit Vector Templates and Reference Voltages

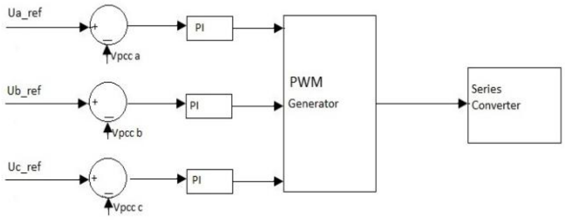

Fig.6 Control Strategy of Series Converter

The series converter of UPQC is responsible to maintain wind farm terminal voltage at a nominal value.

The three phase voltages at PCC contain both fundamental and distorted components. To get unit input voltage vector (U_{abc}), the voltages at PCC are multiplied by gain k= $\frac{1}{V_m}$. Where V_m equal to the peak amplitude fundamental input voltage. These unit voltage vectors are then given to the phased locked loop which generates two quadrature unit vectors ($\sin(wt)$,$\cos(wt)$)

$$U_a = \sin wt \quad (7)$$

$$U_b = \sin(wt - 120) \quad (8)$$

$$U_c = \sin(wt + 120) \quad (9)$$

The unit vector templates which are obtained from the Phase Locked Loop are multiplied with the peak amplitude of fundamental input voltage to get reference voltage signals.

$$U_{abc\_ref} = V_m . U_{abc} \quad (10)$$

The Timer block generates a signal changing at specified transition times. This block is used to generate a logical signal (0 or 1 amplitudes) and control the opening and closing times of power switches like the Breaker block and the Ideal Switch block. This is also used to generate a signal whose amplitude changes by steps at specified transition times. If a signal is not specified at time 0, the output is kept at zero until the first transition time specified in the Amplitude vector.

These reference voltage signals are then compared with the instantaneous voltage at PCC. By comparing these two voltages an error will be generated, this error in voltage is given to the PWM generator to generate the required gate signals for series converter. In such a way, that the series converter compensates the voltage variations at PCC to maintain the wind farm terminal voltage to a nominal value by injecting voltage is in phase with the PCC voltage whenever it is required.

3.2 Static Shunt Compensator

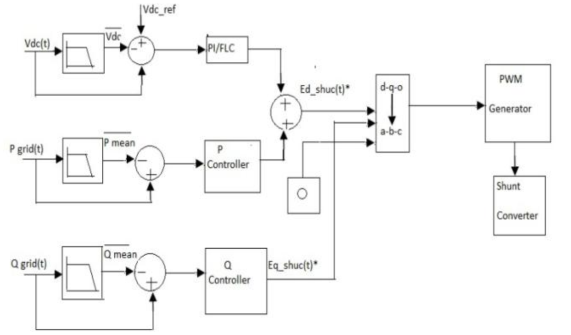

Fig.7 Control Strategy of Shunt Converter

The shunt converter of UPQC is responsible to filter the active and reactive power pulsations generated by the WF.

The mean values of active and reactive powers are obtained by low pass filters and the bandwidth of such filters are chosen so that the power fluctuation components selected for compensation fall into the flicker band as stated in IEC61000- 4-15 standard when the instantaneous values of active and reactive powers are given. The deviations are calculated by subtracting the mean power from the instantaneous power measured in PCC. This controller generates both voltages commands $E_{d\_shuC}*$ and $E_{q\_shuC}*$ based on power fluctuations P and Q, respectively. $E_{d_shuC}*$also contains the control action for the DC–bus voltage loop. This control loop will not interact with the fluctuating power compensation, because its components are lower in frequency than the flicker–band.

The powers P_{shuC} and Q_{shuC} are calculated in the rotating reference frame, as follows:

$$P_{shuC}(t) = 3/2.\, V_d^{PCC}(t).I_d^{shuC}(t)$$

$$Q_{shuC}(t) = -3/2.\, V_d^{PCC}(t).I_q^{shuC}(t) \qquad (11)$$

Ignoring PCC voltage variation, these equations are written as follows.

$$P_{shuC}(t) = k_p^{'}.\, I_{d\_shuC}(t)$$

$$Q_{shuC}(t) = k_q^{'}.\, I_{q\_shuC}(t) \qquad (12)$$

Taking in consideration that the shunt converter is based on a VSI, we need to generate adequate voltages to obtain the currents in (12). This is achieved by using the VSI model proposed in [10], leading to a linear relationship between the generated power and the controller voltages. The resultant equations are:

$$P_{shuC}(t) = k_p^{''}.E_{d\_shuC}*(t)$$

$$Q_{shuC}(t) = k_q^{''}.E_{q\_shuC}*(t) \qquad (13)$$

P and Q control loops comprise proportional controllers, while DC–bus loop uses a PI controller or a Fuzzy Logic Controller

IV. FUZZY LOGIC CONTROLLER (FLC)

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, inference engine and defuzzification.

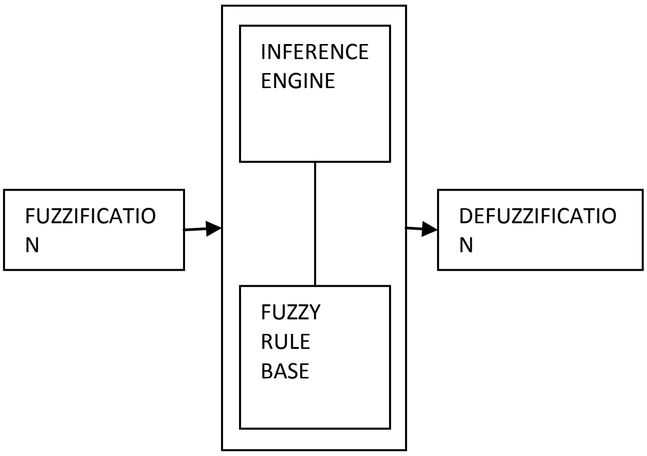

Fig.8 Fuzzy Logic Controller

4.1 Fuzzification

Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PL (Positive Large). The partition of fuzzy subsets and the shape of membership function adapt the shape up to appropriate system.

e/Δe	NL	NM	NS	ZR	PS	PM	PL
NL	NL	NL	NL	NL	NL	NL	NL
NM	NL	NL	NM	NM	NS	NS	NS
NS	NL	NM	NM	NS	NS	NS	ZR
ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR
PS	ZR	PS	PS	PS	PM	PM	PL
PM	PS	PS	PS	PM	PM	PL	PL
PL	PL	PL	PL	PL	PL	PL	PL

Table 1.Rule Base of FLC

4.2 Inference Method

Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

4.3 Defuzzification

As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, "height" method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of Fuzzy Controller are: inputs are error (e), change in error (Δe) and output as shown in Figs. 9(a), 9(b) and 9(c).

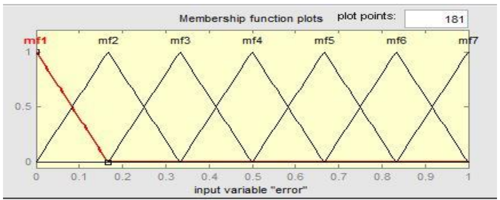

Fig.9(a) Error (e)

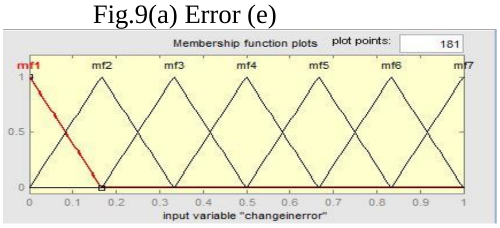

Fig.9 (b) Change in error (Δe)

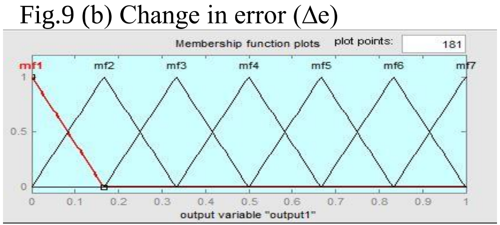

Fig.9(c) Output

V. SIMULATION RESULTS AND DISCUSSION

Case (1): without UPQC
Case (2): with UPQC using PI controller
Case (3): with UPQC using Fuzzy Logic Controller.

By implementing Mat lab/Simulink software simulation was conducted with the following chronology for all the 3 cases:

- At t = 0.0″ the simulation starts with the series converter and the DC–bus voltage controllers in operation.
- At t = 0.5″ the tower shadow effect starts.
- At t = 3.0″ Q and P control loops are enabled.
- At t = 3.5″ L3 load is connected.
- At t = 3.6″ L3 load is disconnected

Case (1): Without UPQC

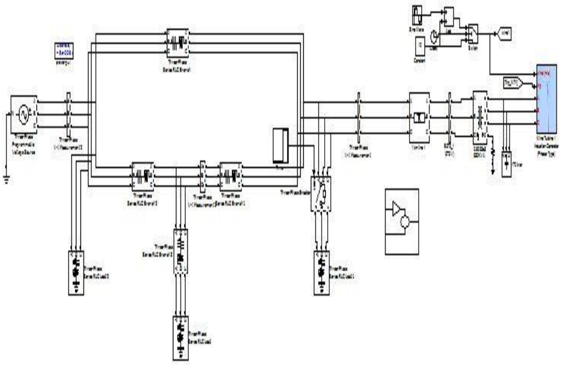

Fig.10 Simulink diagram without UPQC

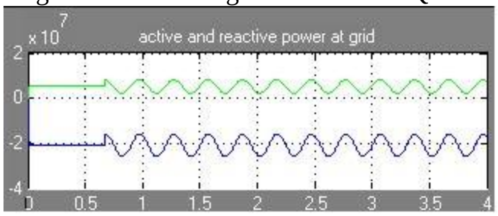

Fig.10 (a) active and reactive power at grid side

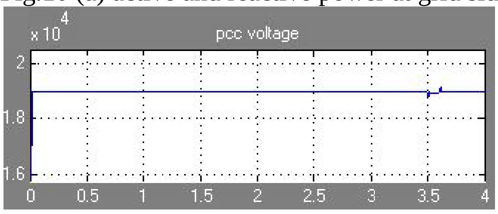

Fig.10 (b) PCC voltage

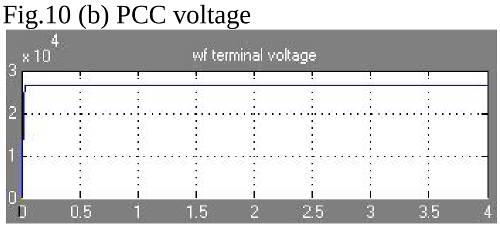

Fig.10(c) Wind farm terminal voltage

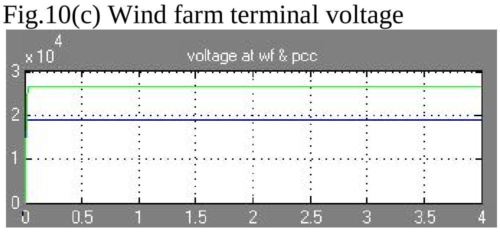

Fig.10 (d) Voltage at wind farm and PCC voltage

Case (2): With UPQC using PI controller:

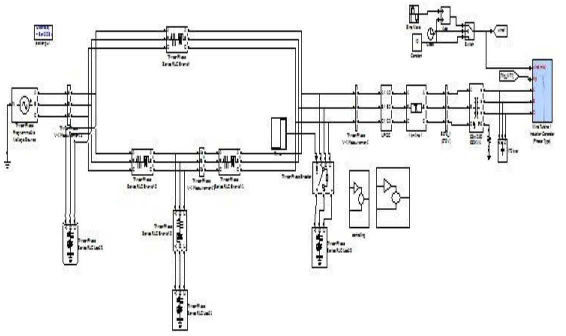

Fig.11 Simulink diagram with UPQC using PI controller

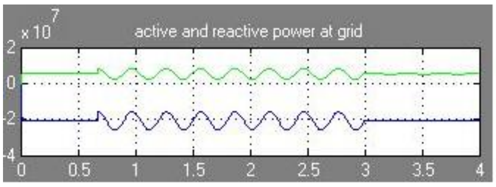

Fig.11 (a) Active and reactive power at grid side

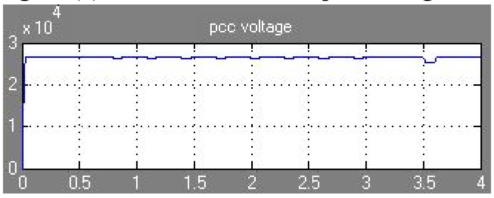

Fig.11 (b) PCC voltage

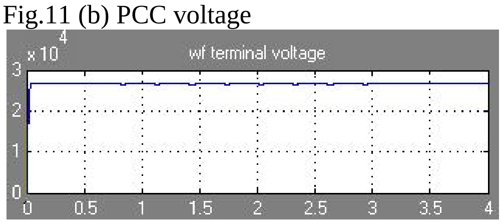

Fig.11(c) Wind farm terminal voltage

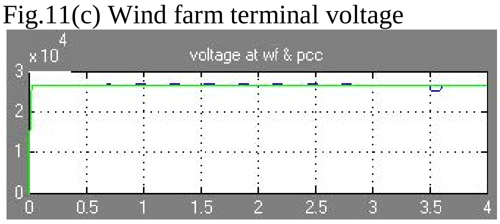

Fig.11 (d) Voltage at wind farm and PCC voltage

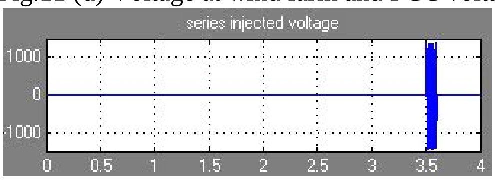

Fig.11 (e) Series injected voltage

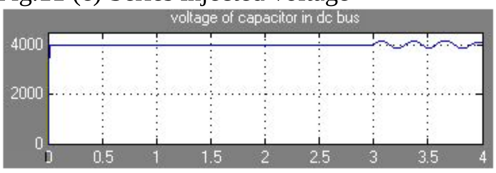

Fig.11 (f) Voltage of capacitor in DC bus

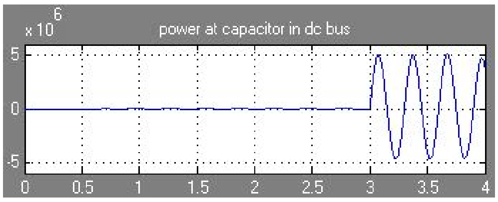

Fig.11 (g) Power of capacitor in DC bus

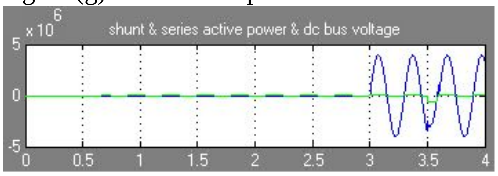

Fig.11 (h) Shunt and series converter active power and DC bus voltage

Case (3): With UPQC using Fuzzy Logic Controller:

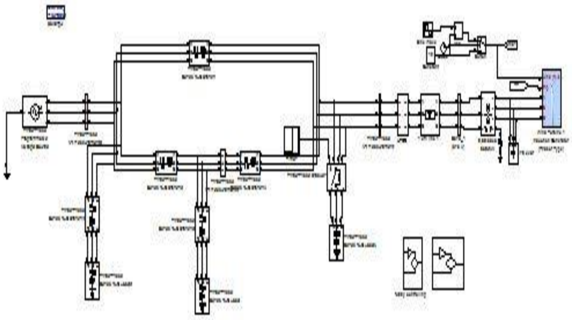

Fig.12 Simulink diagram with UPQC using Fuzzy Logic Controller

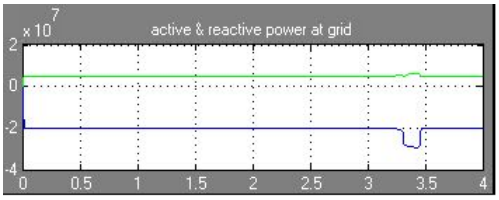

Fig.12 (a) Active and reactive power at grid side

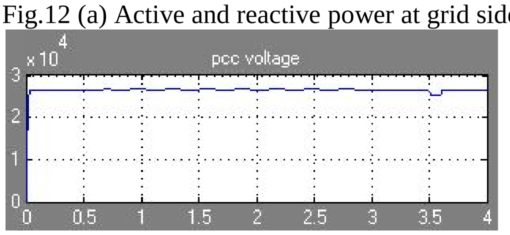

Fig.12 (b) PCC voltage

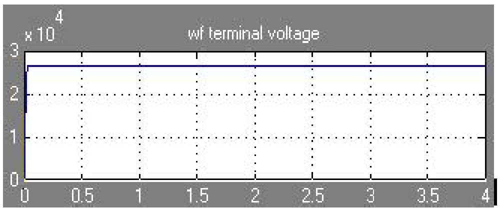

Fig.12(c) Wind farm terminal voltage

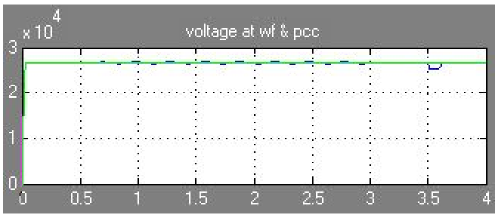

Fig.12(d) Voltage at wind farm and PCC voltage

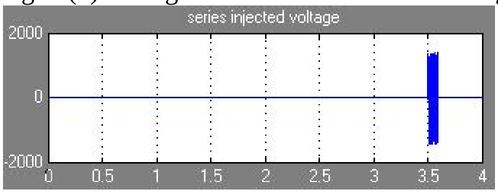

Fig.12(e) Series injected voltage

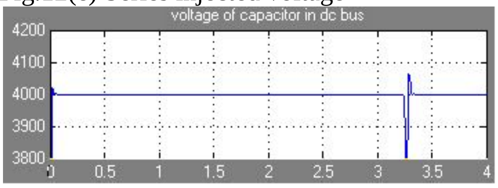

Fig.12(f) Voltage of capacitor in dc bus

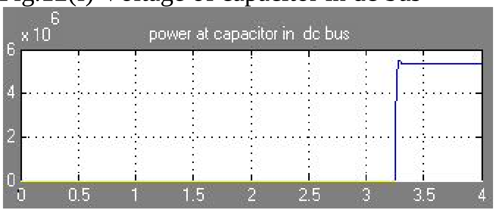

Fig.12(g) Power of capacitor in DC bus

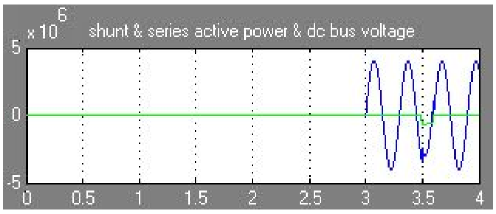

Fig.12(h) Shunt and series converter active power, and DC bus voltage

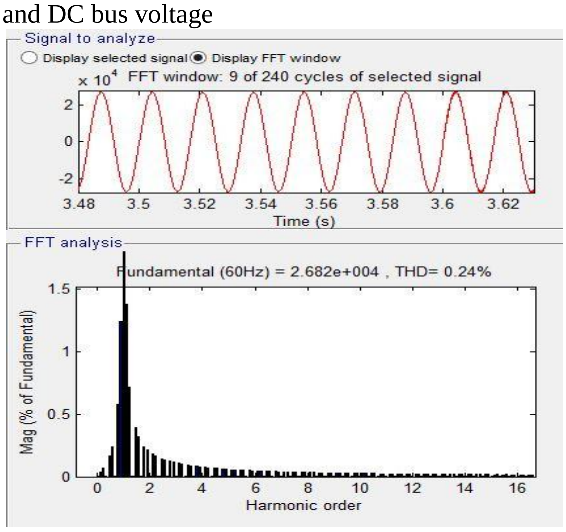

Fig.13 PCC voltage for without UPQC (THD 0.24%)

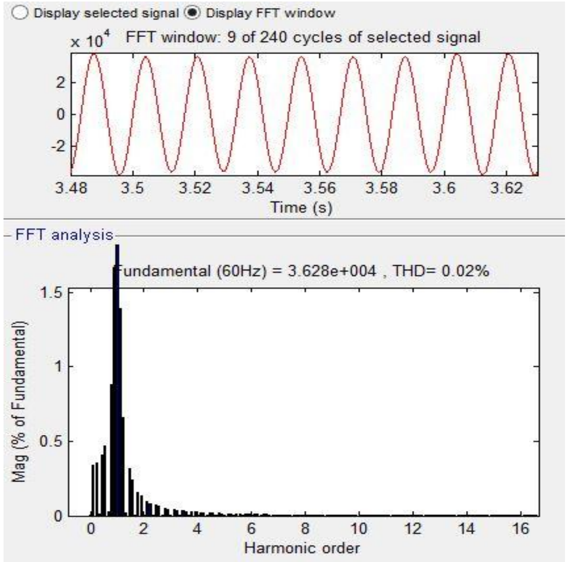

Fig.14 PCC voltage for UPQC with PI Controller (THD 0.02%)

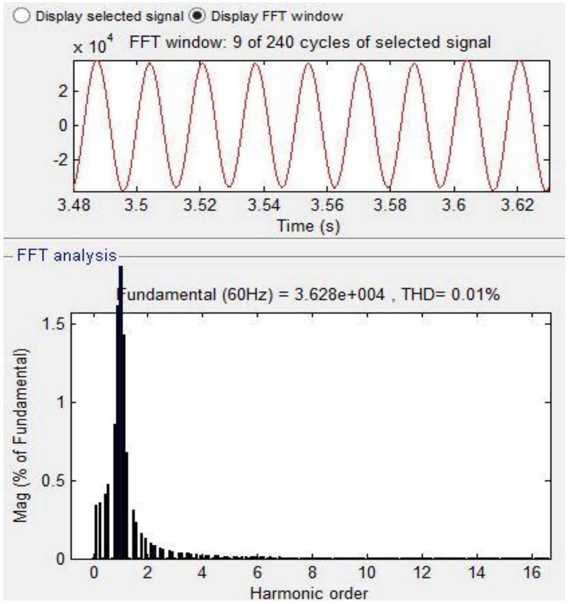

Fig.15 PCC voltage for UPQC with fuzzy logic controller (THD 0.01%)

VI. CONCLUSION

This paper has described a new compensation strategy by using an UPQC type compensator is present to connect SCIG based wind farms to weak distribution power grid. The results are obtained by performing the simulations for without UPQC, UPQC with PI CONTROLLER and UPQC with fuzzy logic controller and compared the PCC voltage of wind farm by calculating total harmonic distortion using FFT analysis. The minimum Total Harmonic Distortion (THD) is observed for UPQC with fuzzy logic controller than that of UPQC with PI CONTROLLER and without UPQC. Hence it is also proved that the dynamic response of UPQC with fuzzy logic controller is faster than that of UPQC with PI controller. So the proposed compensation strategy enhanced the system power quality by rejecting voltage fluctuations.

In future work, performance comparison between different compensator types with different controllers like ANN will be made.

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