RESEARCH ARTICLE OPEN ACCESS

Improvement of Power Quality in Wind Farm Integrated With Weak Grid Using Fuzzy Logic Based UPQC

Mahesh Naik R[1], Dr. T. Gowri Manohar[2]
[1]M.Tech, Dept. of EEE, SVUCE, Tirupati.
[2]Associate Professor, Dept. of EEE, SVUCE, Tirupati.

Abstract
This paper mainly deals with the regulation of voltage at wind farm (WF) terminals and the improvement of power quality and maintenance of WF stability in a WF integrated with Weak-Grid. Generally in modern power systems, the WF is connected through medium voltage (MV) distribution lines. This type of integration results in poor voltage regulation at the point of common coupling (PCC). Thus, the combination of weak grids, wind power fluctuation and system load changes produce disturbances in the PCC voltage, worsening the Power Quality and WF stability. This situation can be improved using Custom power devices technology (CUPS), the Unified Power Quality Compensator (UPQC). The internal control strategy is based on the management of active and reactive power in the series and shunt converters of the UPQC, and the exchange of power between converters through UPQC DC–Link.
In the proposed paper total harmonic distortion (THD) is determined using FUZZY controller and the results are compared with those obtained using PI controller. Simulations results show the effectiveness of the proposed compensation strategy in reducing the THD value there by enhancing Power Quality and Wind Farm stability.
Key words: Wind farm, Weak grid, UPQC, Fuzzy, Simulation.

I. Introduction

The location of generation facilities for wind energy is determined by wind energy resource availability, often far from high voltage (HV) power transmission grids and major consumption centers [1]. Generally in modern power systems, the WF is connected through medium voltage (MV) distribution lines. This type of integration results in poor voltage regulation at the point of common coupling (PCC). The main feature of this type of connections is the increased voltage regulation sensitivity to changes in load [2].

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]. wind resources, turbines employing squirrel cage induction generators (SCIG) have been used since the beginnings. The operation of SCIG demands reactive power, usually provided from the mains and/or by local generation in capacitor banks [4], [5].The changes occur in its mechanical speed due to wind disturbances, This type of integration results in power disturbances propagate into the power system, and can produce a phenomenon known as “flicker”.

In order to reduce the voltage fluctuations that may cause “flicker”, and improve WF terminal voltage regulation, several solutions have been posed. The most common one is to upgrade the power grid, increasing the short circuit power level at the point of common coupling PCC, thus reducing the impact of power fluctuations and voltage regulation problems [5].

In Recent years, the technological development of high power electronics devices has led to implementation of electronic equipment suited for electric power systems, with fast response compared to the line frequency. These active compensators allow 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 [7],[10]. The use of these active compensators to improve power quality and stability with integration of wind energy in weak grids is the approach adopted in this work.

In this paper we propose and analyze a compensation strategy using an UPQC, for the case of SCIG–based WF, common coupling (PCC), caused by system load changes and pulsating WF generated power, respectively. The voltage regulation at WF terminal is conducted using the UPQC series converter, by voltage injection “in phase” with PCC connected to a weak distribution power grid. This system is taken from a real case [8]. The UPQC is controlled to regulate the WF terminal voltage, and to mitigate voltage fluctuations at the point of voltage. On the other hand, the shunt converter is used to filter the WF generated power to prevent voltage fluctuations, requiring active and reactive power handling capability. The sharing of active power between converters is managed through the common

DC link. Simulations were carried out to demonstrate the effectiveness of the proposed compensation approach.

II. System Description & Modeling:

2.1 System Description:

Fig. 1 depicts the power system [1] under consideration in this study. The WF is composed by 36 wind turbines using squirrel cage induction generators, adding up to 21.6MW electric power. Each turbine has attached fixed reactive compensation capacitor banks (175kVAr), and is connected to the power grid via 630KVA 0.69/33kV transformer. This system is taken from and represents a real case. 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 ~ 120MV A this ratio can be calculated.

$$r=\frac{S_{SC}}{P_{WF}} \approx 5.5 \qquad \text{…….. (1)}$$

Values of r < 20 are considered as a "weak grid" connection [3].

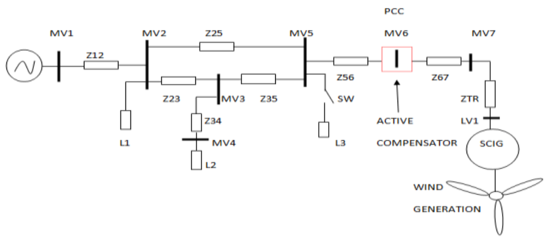

Fig 1. Power system considered

2.2 Turbine rotor and associated disturbances Model:

The power that can be extracted from a wind turbine is determined by the following expression:

$$P=\frac{1}{2}\,.\,\rho.\pi\,.\,R^2\,.\,V^3\,.\,C_P \qquad \text{…….. (2)}$$

Where ρ is air density, R the radius of the swept area, V the wind speed, and *Cp* the power coefficient. For the considered turbines (600kW) the values are R = 31.2 m, p = 1.225 kg/m3 and *Cp* calculation is taken from ref [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

$$P_T = \sum_{i=1\ldots..36} P_i \qquad \text{……… (3)}$$

2.3 Model of induction generator:

For the squirrel cage induction generator the model available in Mat lab/Simulink Sim Power Systems libraries is used. It consists of a fourth–order state–space electrical model and a second–order mechanical model [6].

2.4 Dynamic compensator model:

The dynamic compensation of voltage variations is performed by injecting voltage in series and active–reactive power in the MV6 (PCC) bus bar this is accomplished by using an unified type compensator UPQC. In Fig 2. We see the basic outline of this compensator. The bus bars and impedances numbering is referred to Fig 1. 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 is preferred because of lower DC link losses and faster response in the system than CSI[10]. 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.3. An important feature of this compensator is the operation of both VSI converters (series and shunt) sharing.

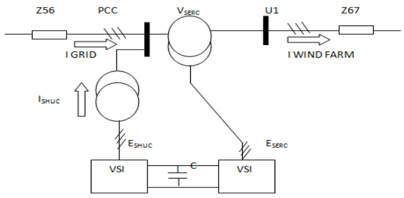

Fig 2. Block diagram of UPQC

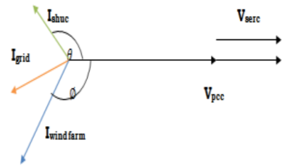

Fig 3.Phasor diagram of UPQC

The same DC–bus, which enables the active power exchange between them. We have developed a simulation model for the UPQC based on these ideas taken from ref [10]. Since switching control of converters is out of the scope of this work, and considering that higher order harmonics generated by VSI converters are outside the bandwidth of significance in the simulation study, the converters are modeled using ideal controlled voltage sources. Fig 4. Shows the adopted model of power side of UPQC. The control of the UPQC, will be implemented in a rotating frame dq0 using Park's transformation (eq.4-5)

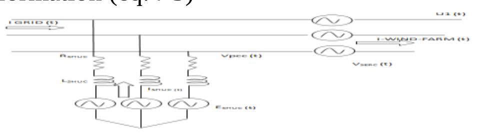

Fig 4.Power stage compensator model.ac side

$$T = \frac{2}{3}\begin{bmatrix} \sin(\theta) & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \text{…. (4)}$$

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = T.\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad \text{……. (5)}$$

Where *f*i=a,b,c represents either phase voltage or currents, and *f*i=d,q,0 represents that magnitudes transformed to the dqo space. This transformation allows the alignment of a rotating reference frame with the positive sequence of the PCC voltages space vector. To accomplish this, a reference angle θ synchronized with the PCC positive sequence fundamental voltage space vector is calculated using a Phase Locked Loop (PLL) system. In this work, an instantaneous power theory based PLL has been implemented [12]. Under balance steady-state conditions, voltage and currents vectors in this synchronous reference frame are constant quantities. This feature is useful for analysis and decoupled control.

III. UPQC CONTROL STRATEGY:

The UPQC serial converter is controlled to maintain the WF terminal voltage at nominal value thus compensating the PCC voltage variations. In this way, the voltage disturbances coming from the grid cannot spread to the WF facilities. As a side effect, this control action may increase the low voltage ride–through (LVRT) capability in the occurrence of voltage sags in the WF terminals [5],[10]. Fig.5 shows a block diagram of the series converter controller. The injected voltage is obtained subtracting the PCC voltage from the reference voltage, and is phase–aligned with the PCC voltage. On the other hand, the shunt converter of UPQC is used to filter the active and reactive power pulsations generated by the WF.

Thus, the power injected into the grid from the WF compensator set will be free from pulsations, which are the origin of voltage fluctuation that can propagate into the system. This task is achieved by appropriate electrical currents injection in PCC. Also, the regulation of the DC bus voltage has been assigned to this converter. Fig 6 shows a block diagram of the shunt converter controller. This controller generates both voltages commands.

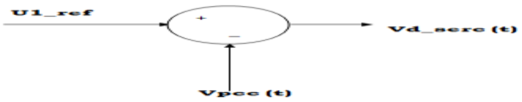

Fig 5.Series compensator controller

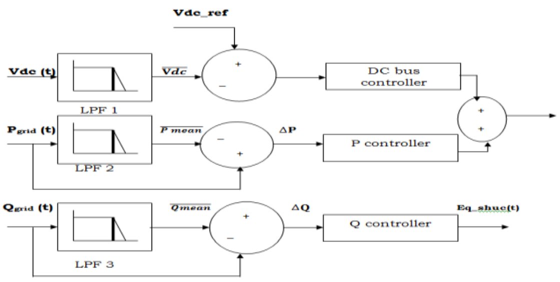

Fig 6.Shunt compensator controller

E_{dshuC} and E_{qshuC} based on power fluctuations P and Q, respectively. Such deviations are calculated subtracting the mean power from the instantaneous power measured in PCC.

The mean values of active and reactive power are obtained by low–pass filtering, 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 turn, E_{dshuC} 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:

$$P_{shu}(t) = \frac{3}{2}.V_d^{PCC}(t)\;.\;I_d^{shuC}(t) \quad \text{…….. (6)}$$

$$Q_{shuC} = -\frac{3}{2}.V_d^{PCC}(t).I_q^{shuC}(t) \quad \text{……. (7)}$$

Ignoring PCC voltage variation, these equations can be written as follows.

$$P_{shuC}(t) = k_p^{'}\;.I_{d_{shuC}}(t) \quad \text{…….. (8)}$$

$$Q_{shu}(t) = k_p^{'}.I_{q_{shuC}}(t) \quad \text{……… (9)}$$

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

$$P_{shuC}(t) = k_p^{''}.E_{D\_shuC}^{*}(\text{t}) \quad \text{…….. (10)}$$

$$Q_{shuC}(t) = k_q^{''}.E_{q\_shuC}^{*}(\text{t}) \quad \text{…….. (11)}$$

P and Q control loops comprise proportional controllers, while DC–bus loop, a PI controller. In summary, in the proposed strategy the UPQC can be seen as a power buffer leveling the power injected into the power

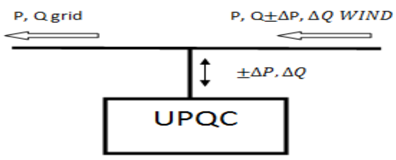

Fig 7.Power buffer concept

System grid. The Fig.7 illustrates a conceptual diagram of this mode of operation. It must be remarked that the absence of an external DC source in the UPQC bus, forces to maintain zero–average power in the storage element installed in that bus. This is accomplished by a proper design of DC voltage controller. Also, it is necessary to note that the proposed strategy cannot be implemented using other CUPS devices like D–Statcom or DVR. The power buffer concept may be implemented using a DSTATCOM, but not using a DVR. On the other hand, voltage regulation during relatively large disturbances cannot be easily coped using reactive power only from DSTATCOM; in this case, a DVR device is more suitable.

IV. 4. IMPLEMENTATION OF FUZZY LOGIC CONTROLLER (FLC)

Fuzzy set theory exhibits immense potential for effective solving of the uncertainty in the problem. It is an outstanding mathematical tool to handle the uncertainty arising due to vagueness. Fuzzy logic control is divided into fuzzification, inference and defuzzification as shown in figure 8.

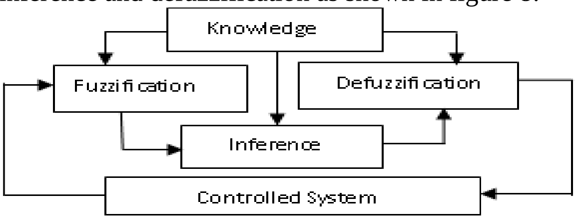

Fig 8: Fuzzy controller block diagram

4.1. Error Calculation:

The error signal (errA) is calculated from the difference between the Current value and the reference value obtained from Repetitive controller. Beside, the error rate signal (RerrA) is the differences between the variation of error at current sampling and its previous sampling. These signals of Current for each phase are measured and converted into per unit (pu.) value.

4.2. FLC:

The section of FLC is divided in three subsections. These subsections are given as summarized in the following:

Fuzzification: The numeric input-variable measurements are transformed by fuzzification part into the fuzzy linguistic variable, which is a clearly defined boundary with a crisp.

The basic if-then rule is defined as "If (error is very small and error rate is very small) then output". The signals error and error rate are described as linguistic variables in the FLC such as large negative (neg), zero (zero), positive (post). These are shown in Fig. In the same way, the input values of the fuzzy controller are connected to the output values by the if-then rules.

The relationship between the input and the output values can be achieved easily by using Takagi-Sugeno type inference method. The output values are characterized by memberships and named as linguistic variables such as negative big (bneg), Negative (neg), zero (zero), positive (post), and positive big (bpost).

Defuzzification: In the defuzzification process, the controller outputs represented as linguistic labels by a fuzzy set are converted to the real control (analog) signals. In the created fuzzy model, "Sugeno"s Weighted Average" method which is the special case of "Mamdani Model" is selected for the defuzzification process.

Signal Processing: The control signals are produced from the output of FLC process. They are used in the generation of switching signals for converter by comparing with carrier signal.

V. DESCRIPTION SIMULATION:

The simulation was conducted with the following chronology:

- 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 = 6.0″ L3 load is connected.
- At t = 6.0″ L3 load is disconnected.

5.1 By Using PI Controller

5.1.1 Compensation of Voltage fluctuation

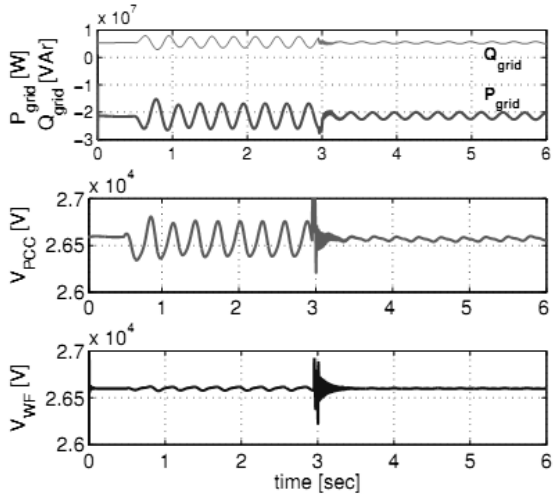

Fig 9 **: (a)** active and reactive power demand at power grid. Middle curve(b): PCC voltage. (c)WF terminal voltages

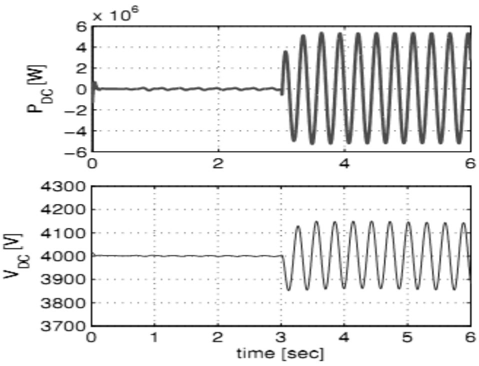

Fig 10:power and voltage of the capacitor in the DC-Bus

In Fig 9 At t = 0.5″ begins the cyclical power pulsation produced by the tower shadow effect. As was mentioned, the tower shadow produces variation in torque, and hence in the active and reactive WF generated power. At t=3.0" the active and reactive power pulsations are attenuated because the P and Q controllers come into action. For nominal wind speed condition, the power fluctuation frequency is f = 3.4Hz, and the amplitude of the resulting voltage variation at PCC, expressed as a percentage is:

$$\frac{\Delta U}{U_{rated}} = 1.50\%$$

This voltage fluctuation is seen in Fig 9. for 0.5 < t < 3. The amplitude of the PCC voltage fluctuation is reduced from its original value of 1.6% (without compensation) to this new value:

$$\frac{\Delta U}{U_{rated}} = 0.18\%$$

This value agrees with IEC standard [13], since is lower than the specified permissible maximum limit, 0.5% at 3.4Hz. In the Fig 8, WF terminal voltage behavior is shown; the series converter action maintains WF terminal voltage constant, regardless of the PCC voltage behavior.

The pulsation of active power at the UPQC DC-side is shown in fig.10.As can be observed in the upper curve, the series converter requires negligible power to operate, while the shunt converter demands a high instantaneous power level from the capacitor when compensating active power fluctuation. Compensation of reactive powers has no influence on the DC side power.

The DC-bus has voltage level limitations in accordance with the VSI's operational characteristics. As the fluctuating active power is handled by the capacitor, its value needs to be selected so that the "ripple" in the DC voltage is kept within a narrow range.

In our case, we have considered a capacitor size C = 0.42 F. This high value can be easily obtained by using emerging technologies based capacitors, such as double–layer capacitors, also known as ultra capacitors.

5.1.2. Voltage regulation:

As been stated in Secc.III, the UPQC is also operated to maintain the WF terminal voltage constant, rejecting PCC voltage variations, due to events like sudden connection/disconnection of loads, power system faults, etc. A sudden connection of load is performed at t = 6″, by closing L3 switch (SW) in Fig.1. This load is rated at PL3 = 9.2MW and QL3 = 9.25MW. Such load is then disconnected at t = 10″.Fig.11 (a) shows the PCC and WF terminal voltages. Fig .11(b) shows series injected voltage at "a" phase.

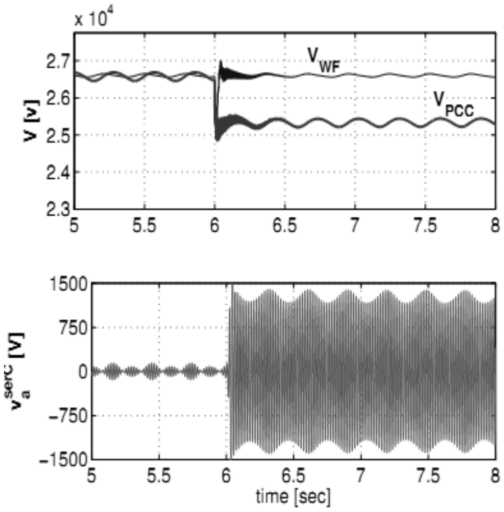

Fig .11. Voltage at wf, at pcc and series injected voltage at "a"phase

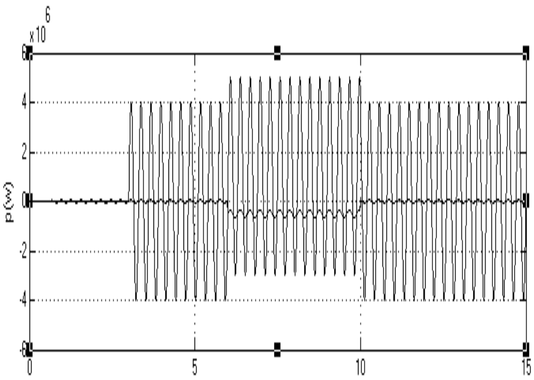

Fig.12**.** Shunt and Series converter active power

In this figure is clearly seen a sudden change in PCC voltage, while WF terminal voltage remains almost constant due to series converter action.

In the above Fig.12 shows the shunt and series converter active–power behavior. The mean power injected (absorbed) by series converter is absorbed (injected) by shunt converter, because of DC voltage regulation loop action (Fig.6). So, the step in series converter active power is the same but opposite sign to that shunt converter power

5.2 By using Fuzzy Controller:

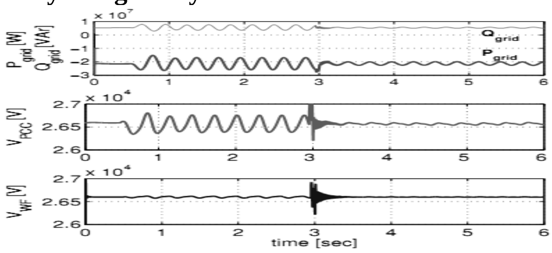

Fig.13 Upper curve: active and reactive power demand at power grid side. Middle curve: PCC voltage. Lower curve: WF terminal

ISSN : 2248-9622, Vol. 3, Issue 6, Nov-Dec 2013, pp.2021-2028

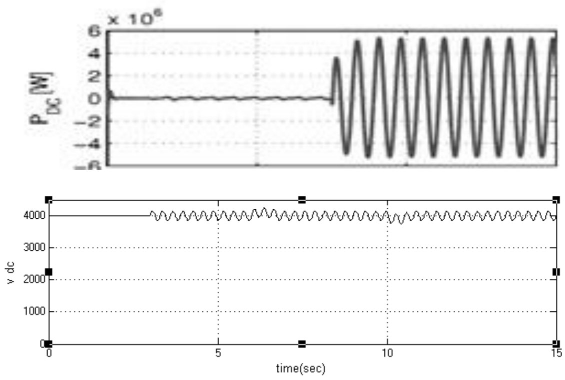

Fig.14. Power and voltage of the capacitor in the DC Bus

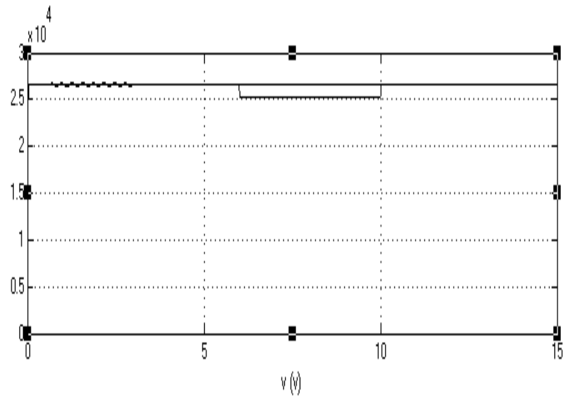

Fig.15.Voltage at WF and PCC

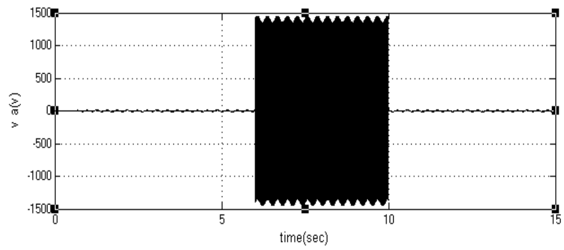

Fig.16.Series injected voltage at”a”phase

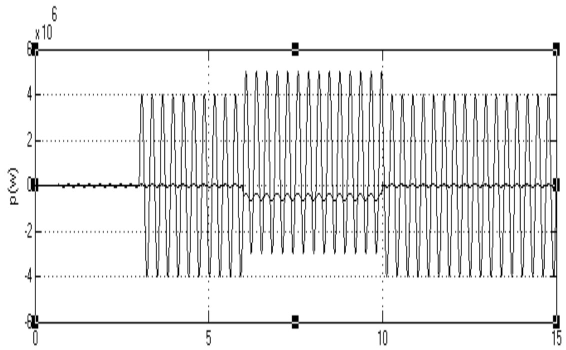

Fig.17.Shunt and series converter active–power; and DC–bus voltage.

5.3. Difference between THD in PI and FUZZY:

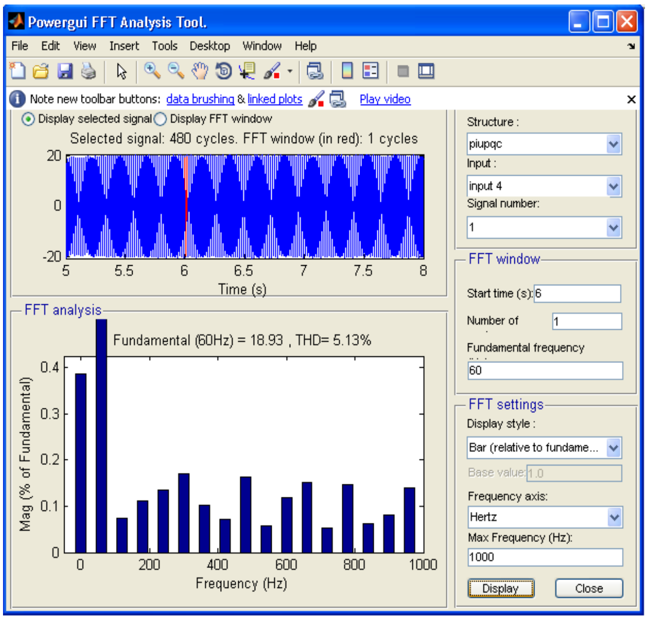

Fig.18.UPQC with PI controller

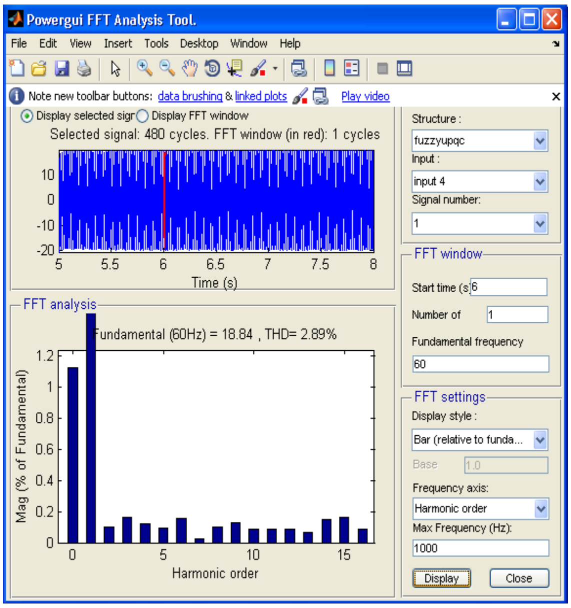

Fig.19.UPQC with Fuzzy logic controller

VI. Conclusion

In this paper, a new compensation strategy was implemented using an UPQC was to connect SCIG based wind farms to weak distribution power grid. The proposed compensation scheme enhances the system power quality, exploiting fully DC–bus energy storage and active power sharing between UPQC converters, features that are not present in DVR and D–Statcom compensators. The THD of fuzzy controller is better than PI controller. The simulation results show a good performance in the rejection of power fluctuation due to “tower shadow effect” and the regulation of voltage due to a sudden load connection. So, the effectiveness of the proposed compensation approach is demonstrated in the case study.

References

[1] M. F. Farias, P.E. Bariattaiotto, M.G. Cendoya" Wind Farm to Weak-Grid Connection Using UPQC Custom Power Device",IEEE 2010.p.p. 978-1-4244-5697.

[2] M.P. P´alsson, K. Uhlen, J.O.G. Tande. "Large-scale Wind Power Integration and Voltage Stability Limits in Regional Networks"; IEEE 2002.p.p. 762–769.

[3] P. Ledesma, J. Usaola, J.L. Rodriguez "Transient stability of a fixed speed wind farm" Renewable Energy 28, 2003 pp.1341–1355.

[4] P. Rosas "Dynamic influences of wind power on the power system". Technical report RISØR-1408. Ørsted Institute. March 2003.

[5] R.C. Dugan, M.F. Mc Granahan, S. Santoso, H. W. Beaty "Electrical Power Systems Quality" 2nd Edition McGraw–Hill, 2002. ISBN 0-07-138622-X.

[6] P. Kundur "Power System Stability and Control" McGraw-Hill, 1994.ISBN 0-07-035958X

[7] N. G. Hingorani y L. Gyugyi. "Understanding FACTS". IEEE Press; 2000.

[8] Z. Saad-Saoud, M.L. Lisboa, J.B. Ekanayake, N. Jenkins and G. Strbac "Application of STATCOM's to wind farms" IEE Proc. Gen. Trans.Distrib. vol. 145, No. 5; Sept. 1998.

[9] T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi "Wind Energy Handbook" John Wiley & Sons, 2001. ISBN 0-471-48997-2.

[10] A. Ghosh, G. Ledwich "Power Quality Enhancement Using CustomPower Devices" Kluwer Academic Publisher, 2002. ISBN 1-4020-7180-9

[11] C. Schauder, H. Mehta "Vector analysis and control of advanced static VAR compensators" IEE PROCEEDINGS-C, Vol.140, No.4, July 1993.

[12] E.M. Sasso, G.G. Sotelo, A.A. Ferreira, E.H. Watanabe, M. Aredes,P.G. Barbosa, "Investigac¸ ˜ao dos Modelos de Circuitos de Sincronismo Trif´asicos Baseados na Teoria das Potˆencias Real e Imagin´aria Instantaneas (p–PLL e q–PLL)", In: Proc. (CDROM) of the CBA 2002 –XIV Congresso Brasileiro de Automtica, pp. 480-485, Natal RN, Brasil,1-4, Sep. 2002.

[13] International Electrotechnical Commission "INTERNATIONAL STANDARD IEC 61000-4-15: Electromagnetic compatibility (EMC) Part 4: Testing and measurement techniques Section 15: Flickermeter Functional and design specifications." Edition 1.1 2003.

[14] H. Akagi, E. H. Watanabe, M. Aredes "Instantaneous power theory and applications to power conditioning", John Wiley & Sons, 2007. ISBN 978-0-470-10761-4.

[15] Sathakkathulla.S and Kumarasabapathy. "Power Quality Improvement using Fuzzy Logic based UPQC" , 2012 ISBN 978-1-4675-2248-9.

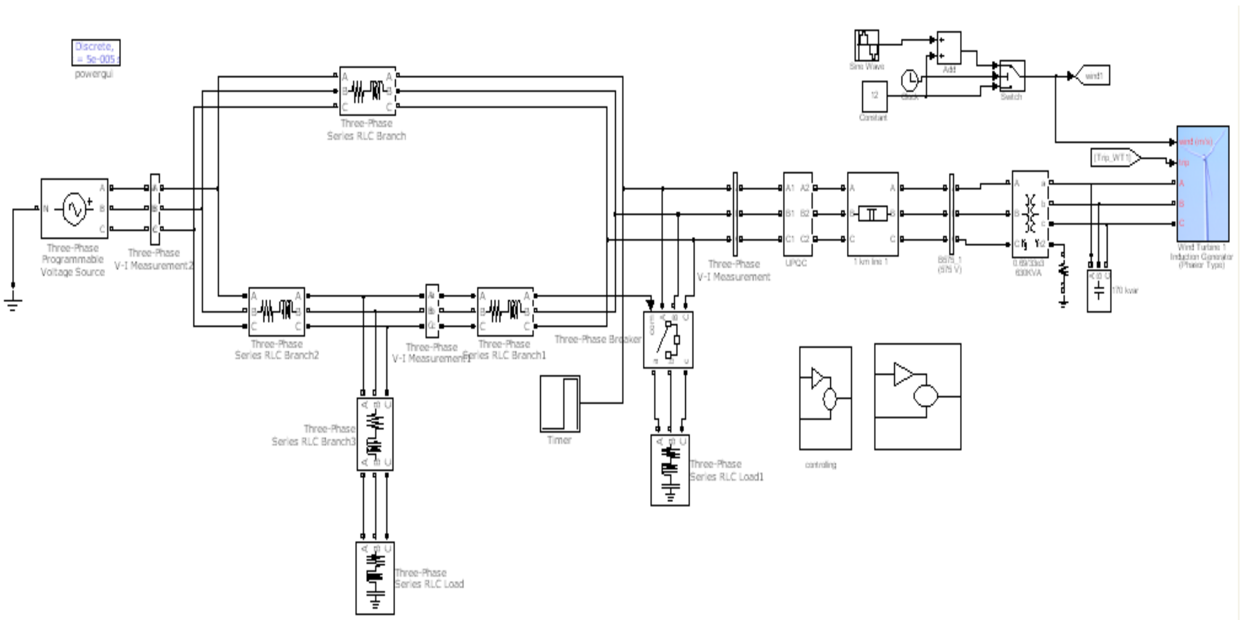

Fig.20.Simulation diagram of wind farm to weak-grid connection

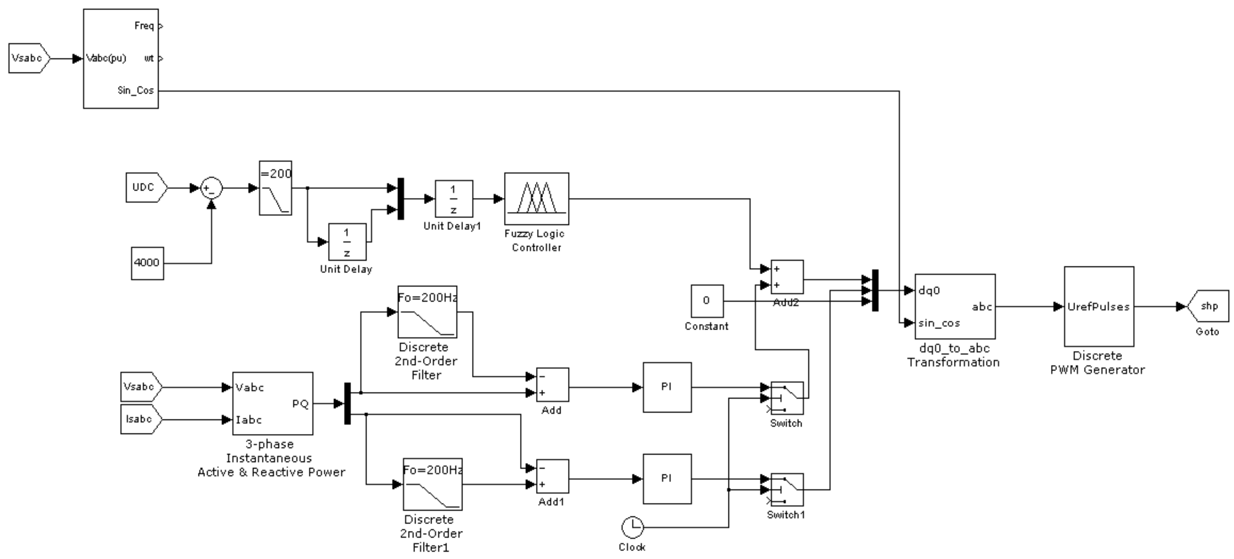

Figure.21. Shunt controller circuit with fuzzy