Enhancement of Power for Wind Farm to Weak Grid Connection

K.Durga Manogna
Department of Electrical and Electronics Engineering
BITIT-Hindupur, Ananthapuramu, Andhra Pradesh, India

V.Lakshma Naik
Department of Electrical and Electronics Engineering
BITIT-Hindupur, Ananthapuramu, Andhra Pradesh, India

Abstract: Wind Farms (WF) employing Squirrel Cage Induction Generator (SCIG) directly connected to the grid represents a large percentage of the wind energy conversion systems around the world. The combination of weak grids, wind power fluctuation and system load changes produce disturbances in the point of common coupling (PCC) voltage, worsening the Power Quality and WF stability. This situation can be improved using control methods at generator level, or compensation techniques at PCC. In case of wind farms based on SCIG directly connected to the grid, is necessary to employ the last alternative. Custom Power Devices Technology (CUPS) result very useful for this kind of application. In this project is based on a particular CUPS device, the Unified Power Quality Conditioner (UPQC). UPQC device was developed to regulate the voltage in the WF terminals, and to mitigate voltage fluctuations at grid side. 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. This approach increases the compensation capability of the UPQC with respect to other custom strategies that use reactive power only. Simulations results show the effectiveness of the proposed compensation strategy for the enhancement of Power Quality and Wind Farm stability.

Keywords – PCC, SCIG, CUPS, UPQC & FACTS.

I. INTRODUCTION

The location of generation facilities for wind energy is determined by wind energy resource availability, often far from HV power transmission grids and major consumption centers. In case of facilities with medium power ratings, the WF is connected through medium voltage (MV) distribution headlines. A situation commonly found in such scheme is that the power generated is comparable to the transport power capacity of the power grid to which the WF is connected, also known as weak grid connection. The main feature of this type of connections is the increased voltage regulation sensitivity to changes in load. So, the system ability to regulate voltage at the PCC to the electrical system is a key factor for the successful operation of the WF. Also, is well known that given 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. Moreover, in exploitation of wind resources, turbines employing 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. In the event that changes occur in its mechanical speed due to wind disturbances, so will the WF active (reactive) power injected (demanded) into the power grid, leading to variations of WF terminal voltage because of system impedance. These power disturbances propagate into the power system, and can produce a phenomenon known as "flicker", which consists of fluctuations in the illumination level caused by voltage variations. Also, the normal operation of WF is impaired due to such disturbances. In particular for the case of "weak grids", the impact is even greater. 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 PCC, thus reducing the impact of power fluctuations and voltage regulation problems. 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 FACTS devices, and
b) enhancing the power quality in distribution systems employing CUPS devices.

The use of these active compensators to improve integration of wind energy in weak grids is the approach adopted in this work. In this project we propose and analyze a compensation strategy using an UPQC, for the case of SCIG–based WF, Connected to a weak distribution power grid. This system is taken from a real case. The UPQC is controlled to regulate the WF terminal voltage, and to mitigate voltage fluctuations at the 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 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. WEAK GRID

The term 'weak grid' is used in many connections both with and without the inclusion of wind energy. It is used without any rigor definition usually just taken to mean the voltage level is not as constant as in a stiff grid. Put this way the definition of a weak grid is a grid where it is necessary to take voltage level and fluctuations into account because there is a probability that the values might exceed the requirements in the standards when load and production cases are considered. In other words, the grid impedance is significant and has to be taken into account in order to have valid conclusions. Weak grids are usually found in more remote places where the feeders are long and operated at a medium voltage level. The grids in these places are usually designed for relatively small loads. When the design load is exceeded the voltage level will be below the allowed minimum and/or the thermal capacity of the grid will be exceeded. One of the consequences of this is that development in the region with this weak feeder is limited due to the limitation in the maximum power that is available for industry etc. The problem with weak grids in connection with wind energy is the opposite. Due to the impedance of the grid the amount of wind energy that can be absorbed by the grid at the point of connection is limited because of the upper voltage level limit. So in connection with wind energy a weak grid is a power supply system where the amount of wind energy that can be absorbed is limited by the grid capacity and not e.g. by operating limits of the conventional generation.

2.1 Basic power control idea

a) Basic Problems with Wind Turbines in Weak Grids- Voltage level

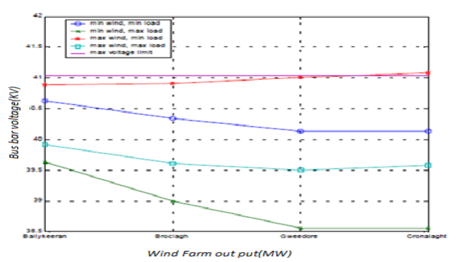

Fig 2.1 Example of voltage profile for feeder with and without wind power

The main problem with wind energy in weak grids is the quasi-static voltage level. In a grid without wind turbines connected the main concern by the utility is the minimum voltage level at the far end of the feeder when the consumer load is at its maximum. So the normal voltage profile for a feeder without wind energy is that the highest voltage is at the bus bar at the substation and that it drops to reach the minimum at the far end. The settings of the transformers by the utility are usually so, that the voltage at the consumer closest to the transformer will experience a voltage, that is close to the maximum value especially when the load is low and that the voltage is close to the minimum value at the far end when the load is high. This operation ensures that the capacity of the feeder is utilized to its maximum. When wind turbines are connected to the same feeder as consumers which often will be the case in sparsely populated areas the voltage profile of the feeder will be much different from the no wind case. Due to the power production at the wind turbine the voltage level can and in most cases will be higher than in the no wind case. As is seen on the figure the voltage level can exceed the maximum allowed when the consumer load is low and the power output from the wind turbines is high. This is what limits the capacity of the feeder. The voltage profile of the feeder depends on the line impedance, the point of connection of the wind turbines and on the wind power production and the consumer load. For a simple single load case the voltage rise over the grid impedance can be approximated with using generator sign convention. This formula indicates some of the possible solutions to the problem with absorption of wind power in weak grids. The main options are either a reduction of the active power or an increase of the reactive power consumption or a reduction of the line impedance.

2.2 Voltage Fluctuations

The main idea is to increase the 2q 3amount of wind energy that can be absorbed by the grid at a certain point with minimum extra cost. There exist several options that can be implemented in order to obtain a larger wind energy contribution. These options include:

- Grid reinforcement
- Voltage dependent disconnection of wind turbines
- Voltage dependent wind power production
- Inclusion of energy buffer (storage)

2.3 Control Strategies

a) Voltage peak limitation

b) Voltage control

2.4 Power Fluctuations

III. UNFIED POWER QUALITY

3.1 Control Objectives of UPQC

The shunt connected converter has the following control objectives

1. To balance the source currents by injecting negative and zero sequence components required by the load
2. The compensate for the harmonics in the load current by injecting the required harmonic currents
3. To control the power factor by injecting the required reactive current (at fundamental frequency)
4. To regulate the DC bus voltage.

The series connected converter has the following control objectives

1. To balance the voltages at the load bus by injecting negative and zero sequence voltages to compensate for those present in the source.
2. To isolate the load bus from harmonics present in the source voltages, by injecting the harmonic voltages
3. To regulate the magnitude of the load bus voltage by injecting the required active and reactive components (at fundamental frequency) depending on the power factor on the source side
4. To control the power factor at the input port of the UPQC (where the source is connected. Note that the power factor at the output port of the UPQC (connected to the load) is controlled by the shunt converter.

IV. SYSTEM DESCRIPTION AND MODELLING

4.1 System Description

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.

$$r=\frac{S_{cc}}{P_{WF}} \approx 5.5 \quad \text{........ (4.1)}$$

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

4.2 Turbine rotor and associated disturbances Model

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

$$P=\frac{1}{2}\,.\rho\pi\,.R^{2}\,.V^{3}\,.C_{p} \quad \text{........ (4.2)}$$

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 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

$$P_T = \sum_{i=1,\ldots,33} P_i \quad \ldots\ldots\ldots (4.3)$$

Moreover, wind speed v in can vary around its average value due to disturbances in the wind flow. Such disturbances can be classified as deterministic and random. The firsts are caused by the asymmetry in the wind flow seen by the turbine blades due to tower shadow and/or due to the atmospheric boundary layer, while the latter are random changes known as turbulence. For our analysis, wind flow disturbance due to support structure (tower) is considered, and modeled by a sinusoidal modulation superimposed to the mean value of v. The frequency for this modulation is 3. Motor for the three–bladed wind turbine, while its amplitude depends on the geometry of the tower. In our case we have considered a mean wind speed of 12m/s and the amplitude modulation of 15%. The effect of the boundary layer can be neglected compared to those produced by the shadow effect of the tower in most cases. It should be noted that while the arithmetic sum of perturbations occurs only when all turbines operate synchronously and in phase, this is the case that has the greatest impact on the power grid (worst case), since the power pulsation has maximum amplitude. So, turbine aggregation method is valid.

4.3 Model of induction generator

For the squirrel cage induction generator the model available in Matlab/Simulink SimPowerSystems libraries is used. It consists of a fourth–order state–space electrical model and a second–order mechanical model.

4.4 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 6.1. We see 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 is 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.4.2. 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. 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 6.3. 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.4.4-4.5)

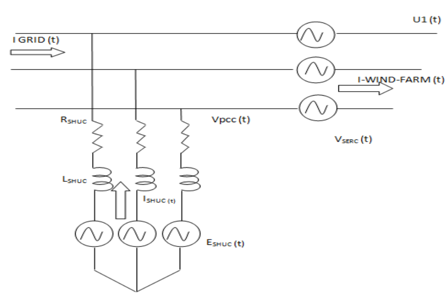

Fig 4.3 Power stage compensator model.AC side

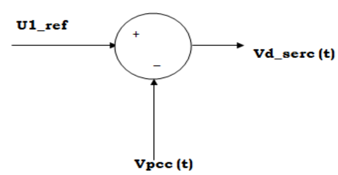

Fig 4.4 Series compensator controller

$$T = \frac{2}{3}\begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad \ldots\ldots (4.4)$$

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = T.\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad \ldots\ldots (4.5)$$

Where fi=a,b,c represents either phase voltage or currents, and fi=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 □ 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. 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.

4.5 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. Fig.4.4 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.4.5 shows a block diagram of the shunt converter controller. This controller generates both voltages commands.

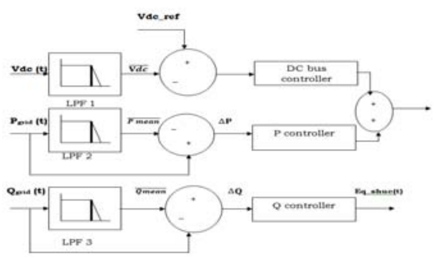

Fig 4.5 Shunt compensator controller

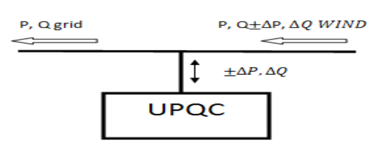

Fig 4.6 Power buffer concept

EdshuC and EqshuC 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, EdshuC 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 PshuC and QshuC are calculated in the rotating reference frame, as follows:

$P_{shu}(t) = \frac{3}{2}.V_d^{pcc}(t) . I_d^{shuC}(t)$ …….. (4.6)

$Q_{shuC} = -\frac{3}{2}.V_d^{pcc}(t).I_q^{shuC}(t)$ …….. (4.7)

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

$$P_{shunt}(t) = k_p \cdot I_{d_{shunt}}(t) \quad \text{........ (4.8)}$$

$$Q_{shunt}(t) = k_p \cdot I_{q_{shunt}}(t) \quad \text{......... (4.9)}$$

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

$$P_{shunt}(t) = k_p \cdot E^{*}_{D\_shunt}(t) \quad \text{........ (4.10)}$$

$$Q_{shunt}(t) = k_p \cdot E^{*}_{q\_shunt}(t) \quad \text{........ (4.11)}$$

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

System grid. The Fig.4.6 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.

V. SIMULATION RESULTS

5.1 Simulation Description

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.

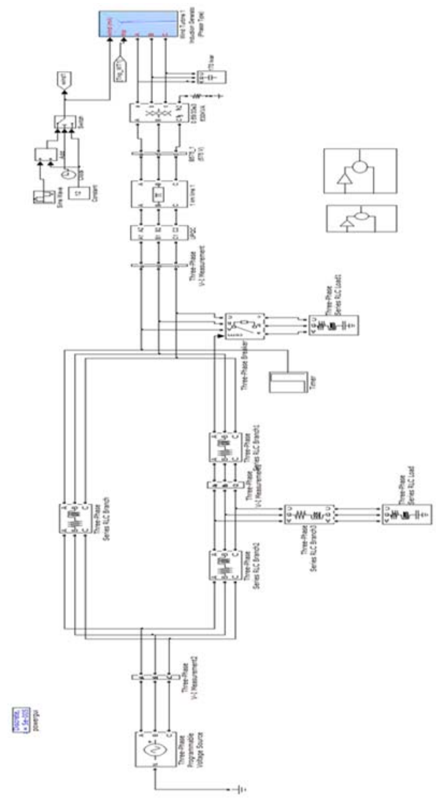

Fig.5.1 .Simulation Diagram of Wind Farm to Weak-Grid Connection

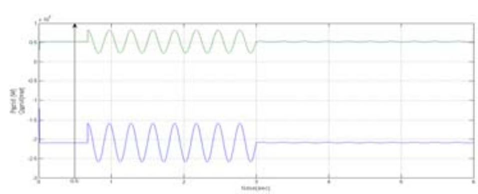

Fig 5.1 Active and Reactive power demand at power grid side

5.2 Output Wave Forms

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.

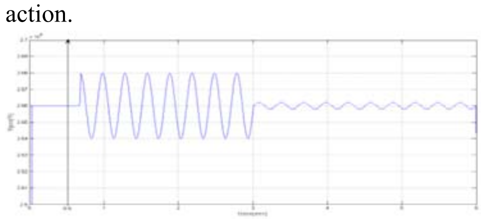

Fig 5.2 PCC voltage

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:

$$\frac{\Delta U}{U_{rated}} = 1.30\%$$

This voltage fluctuation is seen in Fig.5.2 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 [12], since is lower than the specified permissible maximum limit, 0.5% at 3.4Hz.

Fig 5.3 WF terminal voltage

In the Fig.5.3, WF terminal voltage behavior is shown; the series converter action maintains WF terminal voltage constant, regardless of the PCC voltage behavior.

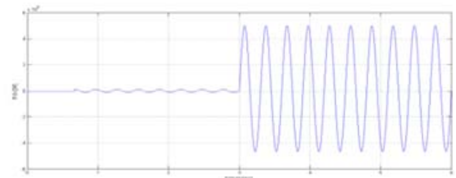

Fig 5.4 Power of the capacitor in the DC–Bus.

The pulsation of active power at the UPQC DC-side is shown in fig.5.4 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.

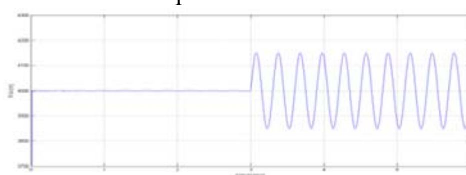

Fig 5.5 voltage of the capacitor in the DC–Bus

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.

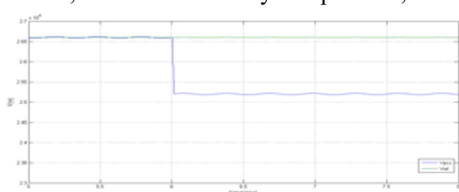

Fig 5.6 Voltage at WF, at PCC

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.5.6 shows the PCC and WF terminal voltages.

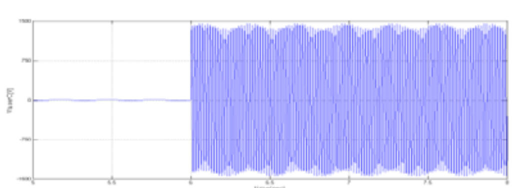

Fig 5.7 series injected voltage at "a" phase

Fig .5.7 shows series injected voltage at “a” phase. In this figure is clearly seen a sudden change in PCC voltage, while WF terminal voltage remains almost constant due to series converter action.

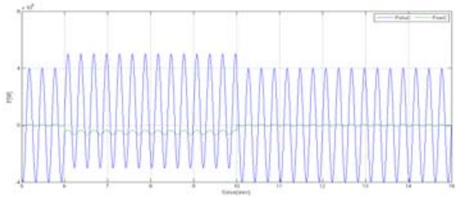

Fig 5.8 Shunt and series converter active–power

In the above Fig.5.8 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.4.5). So, the step in series converter active power is the same but opposite sign to that shunt converter power.

VI. CONCLUSION

In this project, a new compensation strategy implemented using an UPQC was presented, 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 not present in DVR and D–Statcom compensators. 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 study case.
In this project, a new compensation strategy implemented using an UPQC was presented, 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 not present in DVR and D–Statcom compensators. 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 study case.

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