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DIFFERENT CONTROL TECHNIQUES USING UPQC-CONTROLLER FOR DFIG BASED WIND INTEGRATION

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***Abstract*— The integration of wind farms into grid-connected systems introduces several Power Quality (PQ) issues, including voltage unbalance, voltage sag, voltage swell, and harmonics. These problems are primarily caused by non-linear commercial and industrial loads, which act as major sources of harmonic distortion. Among various PQ disturbances, voltage sag accounts for nearly 75% of the issues and is particularly critical for sensitive loads. Such disturbances adversely affect both consumers and manufacturers, highlighting the need for effective PQ improvement. This paper addresses PQ problems such as voltage sag/swell and current harmonics arising from the integration of grid-connected wind turbines and proposes PQ enhancement using a UPQC. To further improve PQ performance, advanced control strategies based on Fuzzy Logic Controller (FLC) are proposed, overcoming the limitations of fixed-gain conventional PI controllers. Simulation results of a Doubly Fed Induction Generator (DFIG)-based grid-connected wind turbine system are presented to compare different control techniques. The proposed FLC-based UPQC demonstrate more effective and efficient mitigation of voltage sag and current harmonics compared to the conventional PI-controlled UPQC, thereby enhancing the reliability of grid-connected wind power systems by ensuring improved power quality.**

***Key Words*— Doubly Fed Induction Generator (DFIG), Unified Power Quality Conditioner (UPQC), Power Quality(PQ), voltage sag, current harmonics, Fuzzy logic,**

1. INTRODUCTION

Now a day's power demand is increasing by faster rate than power generation. Hence the utilities are determined on power generation in order to meet up the increased demand. Out of the total energy demand, 75% load is supplied through fossil fuels. Because of this, there are so many problems related to environment such as greenhouse effect, air pollution, lessening fossil fuels. Hence it is essential to check for another alternative for power generation i.e.

Renewable energy sources. From past ten years, lots of countries have concentrated on these renewable energy sources for power generation. Presently, the government also motivating the public towards the use of renewable energy sources accelerated the renewable energy sector growth. Injecting wind power into the power system grid effects power quality problems such as voltage regulation, reactive power compensation, , harmonics produced in the grid[1].

For the mitigation of both voltage sag and current harmonics, tradition power technology comes into representation. The commonly exercised tradition power device by plentiful researchers for relieving voltage related problems is Dynamic Voltage Restorer (DVR). Due to its tremendous dynamic capability, DVR is well suited to protect sensitive loads from short duration voltage dips or swells [11]. The device STATCOM is mostly used for the restraint of load current harmonics in addition to the involvement of reactive power control [12], but it doesn't take care of voltage related problems. UPQC is the only device widely used for the mitigation of both voltage sag and load current harmonics, thus replacing the functions of two strategy DVR and STATCOM [13]-[15]. The choice of suitable controller plays a essential role to improve the performance of UPQC. To overcome this problem the fuzzy logic and ANN controller is proposed which is best suited for non linear loads, as it works with linguistic variables and it doesn't need any mathematical modeling [16].

Due to the fast improvement and development in manufacture of power electronic converter technology as well as the progress of induction machines specially Double Fed Induction Generators and its advantages of small capacity of converters, high energy and flexible power control, DFIG has been widely used for large-scale wind power generation systems due to its various advantages, such as variable speed operation, controllable power factor, improved power quality and system efficiency. The amount of energy extracted from the wind depends not only on the occurrence wind speed, but also on the control system applied on the wind energy conversion system [2]

In the proposed work, the PQ problems voltage sag and current harmonics are simulated and analyzed in the grid connected wind power system. To improve PQ, the proposed FLC controller based UPQC is implemented for effectual and efficient mitigation of both voltage sag and current harmonics. The performance of the planned system is validated by comparing the simulation results with conventional PI controlled UPQC.

Considering the prime mover quality, the wound rotor induction machine with field-oriented control is very attractive for high performance variable speed generation application. In this electric generator group, the speed of the prime mover is permissible to be different within a certain range (subsynchronous and supersynchronous mode) and the output of electrical power is all times maintained at constant voltage and constant frequency by controlling the slip power from the rotor terminals. Another fundamental feature of this arrangement is that the power converters have to handle the slip power and thus their rating is only a fraction of the total power system. The active and reactive power control system of the wind turbine with DFIG and back-to back converter connected to the electric grid is shown in Fig. 1.

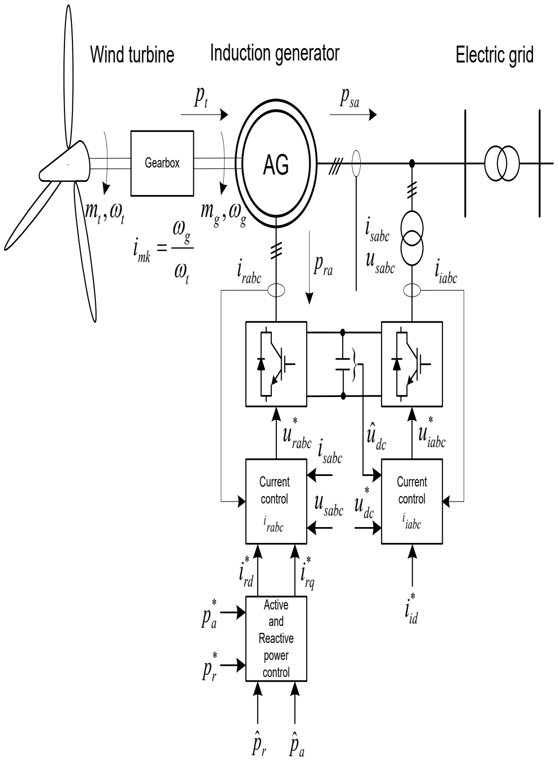

Fig.1. Wind turbine control system with DFIG

The main rule of DFIG is alteration of power given from the wind turbine p_t to the electric power p_{sr} and electric power delivery from DFIG stator to the electric grid. The wind power is particularly variable value depending about the wind speed, so DFIG from the wind turbine side has variable turbine torque m_t and turbine angular speed ω_t, i. e. generator torque mg and generator angular speed ω_g. Simplified observed, electric grid has basically constant voltage u_{mabc} and constant angular frequency ωs. Operational conditions of the wind turbine based on primarily equation that describes relationship of the angular frequencies of the stator and rotor speed $\omega_s=\omega_g+\omega_r$, give control system of the generator. Thereat, there are variable stator losses $p_{Cus,}$ rotor losses p_{Cur}. And active rotor power p_{ra}. Stator active power p_{sa} determines set value of the reference active power p_a^*. So, rotor active power p_{ra} is the significance of reference value p_a^* for defined wind turbine power. Induction generator can work in all the mode as a super-synchronous mode (p_{ra}<0), sub-synchronous mode (p_{ra}>0) and synchronous mode (p_{ra}=0).

2. MODELING OF THE ACTIVE AND REACTIVE POWER CONTROL SYSTEM OF THE DFIG WIND TURBINE

2.1 Modeling of the wind turbine drive train

Dynamical model of the wind turbine describes the major parts of the wind turbine drive train system and induction generator that contribute in interaction of the wind turbine with electric power system. By modeling of the drive train system it is require apply two-mass model. Accordingly, low frequency torsion fluctuations that dominate in dynamic performance of the wind turbine can be accepted. Model of the drive train include inertias of the wind turbine, generator and gearbox which attach two rotating masses.

In this paper is chosen well-known by two-mass model of the wind turbine and generator drive train. The small mass of the induction generator is represented by inertia J_g and the grate mass of the wind turbine is represented by inertia J_t.

The system of equations for simulation of the wind turbine drive train described in base quantities is:

$$\left.\begin{aligned} & d\vartheta_t / dt = \omega_t \\ & d\vartheta_g / dt = \omega_g \\ & d\omega_t / dt = \left(D_{vtt}\omega_g + K_{vtt}\vartheta_g - D_{vtt}\omega_t - K_{vtt}\vartheta_t - m_t\right)/T_t \\ & d\omega_g / dt = \left(-D_{vtt}\omega_g - K_{vtt}\vartheta_g + D_{vtt}\omega_t + K_{vtt}\vartheta_t + m_g\right)/T_g \end{aligned}\right\} \tag{1}$$

Where

$$m_t = P_t / \omega_t \tag{2}$$

Time constants of the induction generator T_g and wind turbine $T_{t,}$ damping coefficient D_{vtt} and shaft stiffness K_{vtt} in equations system (1) are:

$$\left.\begin{aligned} & T_t = (J_t\omega_b^2)/(P_b i_{mk}^2 p^2) \\ & T_g = (J_g\omega_b^2)/(P_b p^2) \\ & D_{vtt} = (D_{vt}\omega_b^2)/(P_b i_{mk}^2 p^2) \end{aligned}\right\}$$

and $K_{vtt} = (K_{vt}\omega_b)/(P_b i_{mk}^2 p^2)\,[pu]$, where i_{mk} is gearbox ratio.

Model input values are: v_w – wind speed that defines wind turbine electric power upon Fig. 1., m_g – electromagnetic torque and m_t – wind turbine torque of induction generator obtained from dynamic model of DFIG.The state variable of wind turbine dynamic model, whose at the same time output values, are: ϑ_g – angle of rotor of induction generator, ϑ_t – angle of the wind turbine axis and ω_g – angular speed of induction generator.

2.2 Dynamic model of the DFIG

In the wind turbine system connected to the grid side with vector control of active and reactive power of DFIG, usually is used transformation of current, voltage and magnetic fluxes vectors of stator and rotor from original abc reference frame into two-phase rotating dq reference frame.

Dynamic functioning modes of induction generator be able to described by the differential equations system for stator and rotor windings and the equation of rotor motion. The solutions of these equations describe dynamic characteristics of the machine.

The differential equations of the induction machine stator and rotor windings defined in vector mode and in dq rotating reference frame by angular speed ω_k are [4]:

$$\bar{u}_{sdq} = \bar{i}_{sdq} R_s + \frac{d\bar{\psi}_{sdq}}{dt} + j\omega_k \bar{\psi}_{sdq}, \qquad (3)$$

$$\bar{u}_{rdq} = \bar{i}_{rdq} R_r + \frac{d\bar{\psi}_{rdq}}{dt} + j(\omega_k - \omega)\bar{\psi}_{rdq}, \qquad (4)$$

where: ω – angular rotor speed.

Relationships between vectors of magnetic fluxes and vectors of stator and rotor currents are:

$$\bar{\psi}_{sdq} = L_s \bar{i}_{sdq} + L_m \bar{i}_{rdq}, \quad \bar{\psi}_{rdq} = L_m \bar{i}_{sdq} + L_r \bar{i}_{rdq}. \qquad (5)$$

By substituting vector of stator current $\bar{i}_{sdq}$ and vector of rotor current $\bar{i}_{rdq}$ in equations (3) and (4) with vectors of magnetic fluxes of stator $\bar{\psi}_{sdq}$ and rotor $\bar{\psi}_{rdq}$ become:

$$\bar{u}_{sdq} = \frac{d\bar{\psi}_{sdq}}{dt} + \left(\frac{1}{T_s'} + j\omega_k\right)\bar{\psi}_{sdq} - \frac{k_r}{T_s'}\bar{\psi}_{rdq}$$

$$\bar{u}_{rdq} = \frac{d\bar{\psi}_{rdq}}{dt} - \frac{k_s}{T_r'}\bar{\psi}_{sdq} + \left(\frac{1}{T_r'} + j(\omega_k - \omega)\right)\bar{\psi}_{rdq}$$

(6)

The equivalent diagram of the three-phase induction machine for dynamic states, given from equations (3) to (6), is shown in Fig. 3.

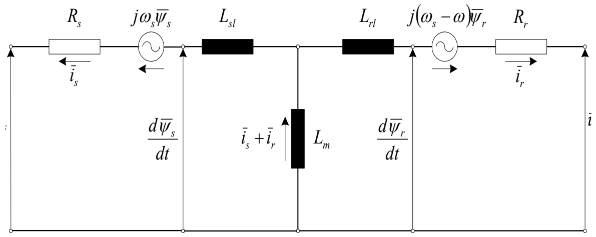

Fig.2 Equivalent diagram of the induction machine for dynamic states

The parameters presented in equations (3) to (6) are: $L_s' = \sigma L_s$, $L_r' = \sigma L_r$, $\sigma = 1 - L_m^2 / L_s L_r$, $k_s = L_m / L_s$, $k_r = L_m / L_r$, $T_s' = L_s' / R_s$ and $T_r' = L_r' / R_r$.

Equation of electromagnetic generator expressed in base quantities is:

$$m_g = \frac{k_r}{L_s'}(\psi_{sq}\psi_{rd} - \psi_{sd}\psi_{rq}). \qquad (7)$$

Current active and reactive power of induction generator is specified from the product of stator voltage vector and complex conjugate vector of stator current:

$$p_a = u_{sd} i_{sd} + u_{sq} i_{sq}, \qquad (8)$$

$$p_r = u_{sq} i_{sd} - u_{sd} i_{sq}. \qquad (9)$$

Choice of the reference frame angular speed depends on preferred configuration of DFIG control system connected to the electric grid. Since, for control system realization of the converter connected to the rotor side and converter connected to the grid side necessary apply different reference frames it is selected αβ reference frame (ω_k=0) as a basic frame for mathematical model of the electric components in power circuits of the wind turbine.

The input values from vector equations (6) are vector of stator supply $\bar{u}_{sdq}$ and vector of rotor supply $\bar{u}_{rdq}$. The state variables, at the similar time output values, are vectors of magnetic fluxes of stator $\bar{\psi}_{sdq}$ and rotor $\bar{\psi}_{rdq}$. Other output values are vectors of stator and rotor currents and electromagnetic torque of generator.

Dynamic model of the DFIG is expressed in αβ reference frame, and all the inputs and outputs of model are expressed in that reference frame. The parameters of DFIG generator and base quantities are shown in appendix.

3. GRID INTEGRATED DFIG BASED WIND POWER SYSTEM - POWER QUALITY ISSUES AND THEIR IMPACTS

3.1 Proposed Methodology

The proposed work in the power grid is interconnected with Doubly Fed Induction Generator (DFIG) based wind Turbine and is coordinated in terms of voltage and frequency. The wind speed is kept as 15m/s which are regarded as nominal value which may differ from 8 to 15 m/s due to fluctuations. The PQ problems voltage sag is simulated by creating three phase to ground fault and the load current harmonics are simulated by connecting Diode bridge rectifier load in the proposed grid connected wind power system. For PQ improvement, UPQC is designed for the above mentioned problems and the proposed control strategy using FLC is implemented for the generation of both reference voltage for series inverter and the reference current for shunt inverter which provides an efficient mitigation of both supply side and also loads side disturbances, thus keeps the PQ in a grid connected wind power system as per IEEE norms. The effectiveness of the proposed FLC based UPQC by comparing the simulation results with the conventional PI controller based UPQC.

3.2. UNIFIED POWER QUALITY CONDITIONER

UPQC is a tradition power device which is accountable for the alleviation PQ disturbances in both supply and load side. The schematic diagram of UPQC is shown in consists of two Voltage Source Inverters (VSI) series and shunt, tied back to back with each other sharing a common dc link. The shunt inverter is controlled in current control mode such that it delivers a current which is equal to the set value of the reference current as governed by the UPQC control algorithm and also to maintain the dc bus voltage at a set reference value

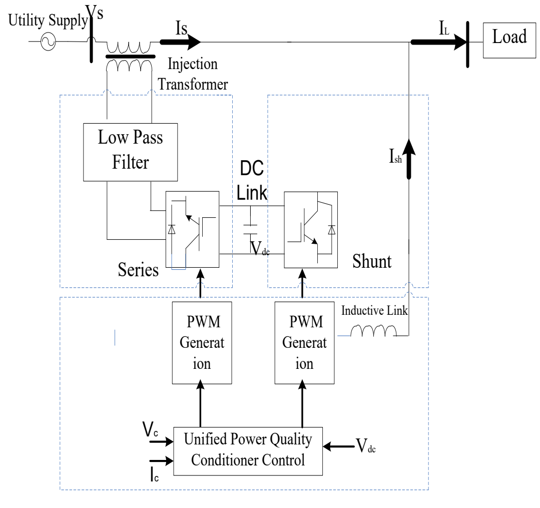

Fig.3 UPQC Controller

3.3 Methodology using UPFC Controller

In this work the performance of UPQC is enhanced by developing a new control strategy using FLC. The advantages of FLC over the conventional controller are that FLC even works without a perfect mathematical model. Also FLC is able to handling nonlinearity and is more robust compared to conventional PI controller which also improves the performance of UPQC. The control strategy used in this work is described below.

3.3.1 Conventional PI Control Strategy

In this control strategy, both shunt and series APF in UPQC is controlled with conventional PI controller. In Series controller the gain values P and I are chosen as Kp = 10 and Ki = 0.1 using trial and error method. In Shunt It is Kp = 18.3 and Ki = 4.3. In series APF, the faulted sag voltage is compared with the reference voltage. The error voltage is processed through PI controller and its output is converted to three phase through unit vector generation, then it is fed into Pulse Width Modulation (PWM) generator to provide gate pulses to Series APF such that this can be able to inject the required voltage for the mitigation of voltage sag.

In Shunt APF, the harmonic load current is compared with the reference current and the error is processed through PI controller. Its output is converted to three phase and it is fed into Hysteresis controller for providing gate pulses to Shunt APF which is capable of mitigating load current harmonics.

3.3.2 Fuzzy Logic Controller

FLC is one of the most successful operations of fuzzy set theory. Its principal aspects are the exploitation of linguistic variables rather than numerical variables. FL control technique relies on human potential to figure out the systems behavior and is constructed on quality control rules. FL affords a simple way to turn up at a specific conclusion based upon distorted, uncertain, inaccurate, noisy, or missing input data.

Fig. 4 shows the block diagram of proposed fuzzy logic control scheme of three phase PWM rectifier. The dc-bus voltage Vdc is sensed and compared with a reference value Vdc*. The obtained error e (k) =Vdc* (k)-Vdc (k) and its incremental deviation δe (k) = e (k) - e (k-1) at the k^{th} sampling instant are used as inputs for fuzzy controller. The DC bus voltage is controlled by adjusting the PWM control pulses using fuzzy controller.

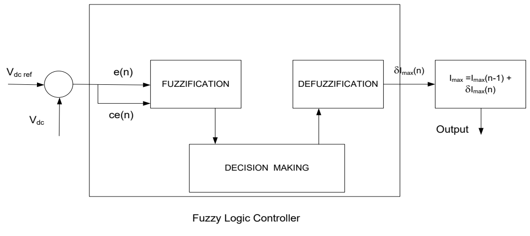

Fig.4 Fuzzy control blocks

The main characteristics of the fuzzy control are the following:

- Seven fuzzy sets for each of the two inputs;
- Nine fuzzy sets for the output;
- Triangular membership function;
- Fuzzification using continuous universe of discourse;
- Implication using Mumdani's min operator;
- Defuzzification using centroid method.

The input fuzzy variables have the same membership functions. The fuzzy control has seven membership functions called from negative big (NB) to positive big (PB) and the output fuzzy variable have nine membership functions called from positive very big (PVB) to negative very big (NVB).The basic structure of an FLC is represented in Fig 7.

A Fuzzification interface change the input data into suitable linguistic values.

A Knowledge Base which comprises of a data base along with the necessary linguistic definitions and control rule set.

A Decision Making Logic which collect the fuzzy control action from the information of the control rules and the linguistic variable descriptions.

A Defuzzification interface which surrenders a non- fuzzy control action from an conditional fuzzy control action.

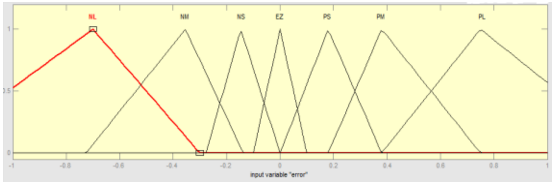

Fig. 5 Membership function of input variable 'error'

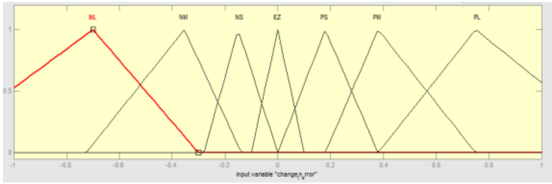

Fig. 6 Membership function of input variable 'change in error'

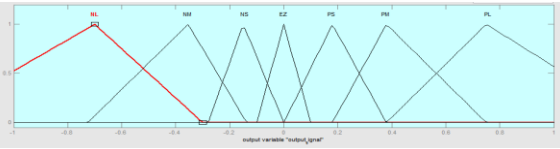

Fig 7 Basic structure of Fuzzy Logic controller

In this paper, an superior control strategy, FLC is implemented along with UPQC for voltage correction during Series APF and for current regulation Shunt APF. Error and Change in Error are the inputs and Duty cycle is the output to the Fuzzy Logic Controller. In the decision-making process, there is rule base that links between input (error signal) and output signal. Figure 8, shows the rule base exercised in this proposed Fuzzy Logic Controller.

ce / e	NB	NS	Z	PS	PB
NB	PB	PS	NS	NS	NB
NS	PS	PS	NS	PB	NB
Z	NB	NB	NS	PS	PB
PS	NS	NS	PB	NB	PS
PB	NS	NS	PB	PB	PB

Fig 8 Fuzzy Rule Representation

4 SIMULATION RESULTS

The proposed system is implemented by integrating 120 kV power grid with 1.5 MW, 575 V DFIG based wind turbine and also synchronized with respect to voltage and frequency using MATLAB Simulink. The effectiveness of the proposed system is validated by three different cases. The simulation of PQ problems and the execution of UPQC along with proposed FLC and conventional PI controller are shown by the subsequent cases.

4.1. Uncompensated System

In the proposed system, the voltage sag and swell is simulated by creating three phase to ground fault in the time interval of 2.5s to 5*10^4 sec and is shown in Fig 1. The nonlinear load is connected which makes load current harmonics in a grid connected wind power system and is shown Fig 10. The Total Harmonic Distortion (THD) of the source current without uncompensated system and with different types controller are obtained by the FFT analysis as shown in Fig 11.

4.2 Analysis of UPQC-DFIG with PI Controller

The tradition power device UPQC-DFIG is implemented with conventional PI controller to compensate both voltage sag and load current harmonics in the proposed system. The values of P and I are chosen by trial and error method appropriate for compensation. The simulation results for both load voltage and source current is shown in Fig 12. The THD spectrum for load current is also shown in Fig 12 Voltage and Current Waveforms of Compensated System with PI controller and Fig 13 THD level of Source Current with PI controller

4.3 Analysis of UPQC-DFIG with Fuzzy Logic Controller

The detailed Simulation of the Proposed UPQC-DFIG with Fuzzy Logic Controller is shown in Fig 11 and the design values are also shown in Table 6.1. The proposed Fuzzy Logic controller based UPQC is put into service to compensate both voltage sag and load current harmonics. The simulation end results for both load voltage and source current is shown in Fig.14 and THD for load current is also shown in Fig 15.

4.4. Performance Comparison of Different Control Strategies

The implementation of UPQC controller with different control strategies for alleviating both voltage sag and load current harmonics is implemented in a DFIG based grid connected wind power system. The success of system is proven by comparing the proposed control strategy with conventional PI controller. The performance comparison results in source current THD with UPQC Fuzzy logic controller, PI Controller and without UPQC are are shown in Table 6.2.

Different Configuration System	Source Current THD in Percent
Uncompensated System	57.55
UPQC with PI Controller	6.80
UPQC with Fuzzy Logic Controller	1.36

Table 6.2 Performance of Different Types Controller

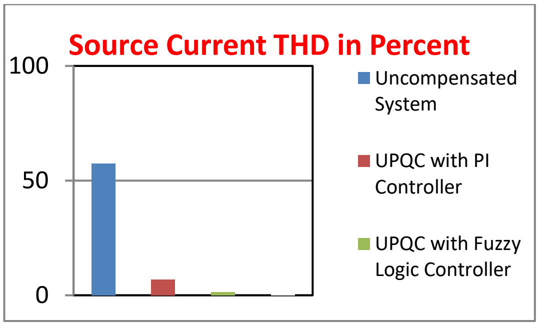

Fig.9 THD of current under different controller

By comparing the THD of load current, UPQC with PI Controller the source current harmonics achieved is 6.80% and the UPQC with Fuzzy Logic Controller the source current harmonics achieved is 1.36%. which shows result that the FLC controller give the effective and proficient compensation for both voltage sag and current harmonics. Thus the performance of UPQC is greatly improved by completely mitigating voltage sag and also the THD of load current is drastically diminished and is kept within acceptable IEEE norms.

Without controller sag_swell

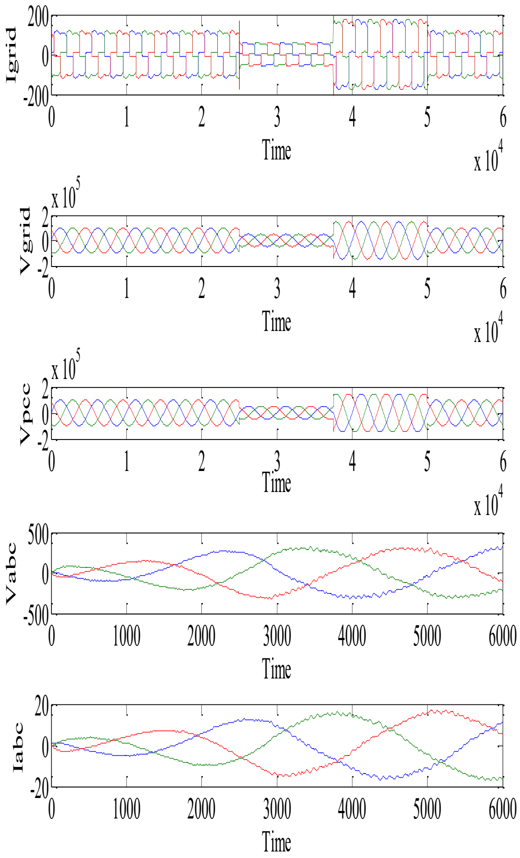

Fig.10 voltage and current waveform of load side, source side and point of comman coupling without controller

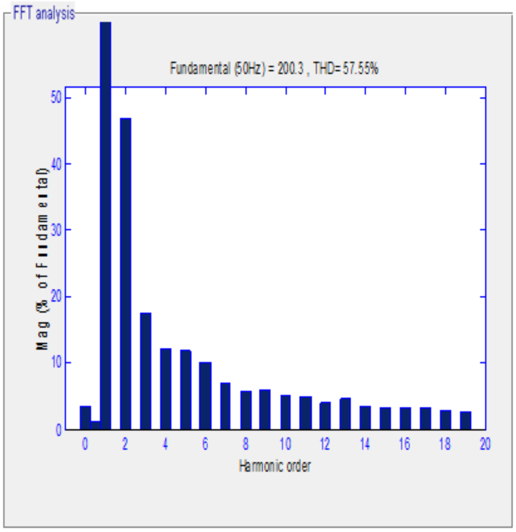

Fig.11 THD of Source Current without Controller

With PI UPQC

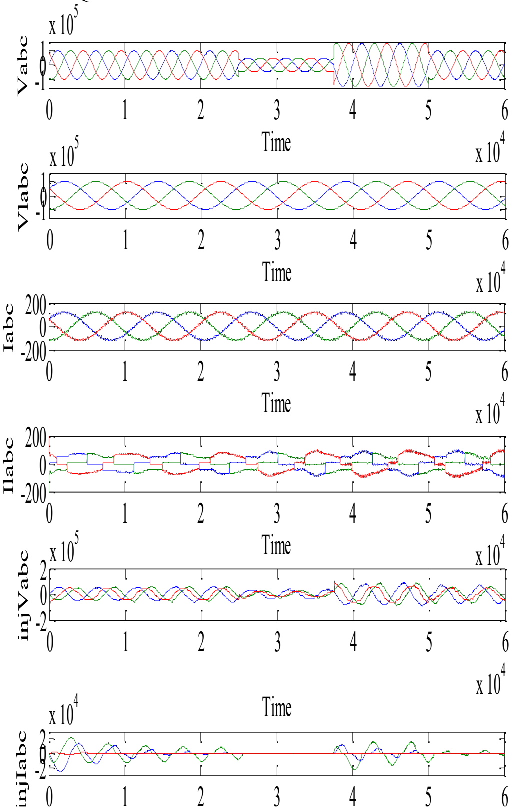

Fig.12 Voltage and Current Waveform of Load Side, Source Side and Injected Side with PI Controller

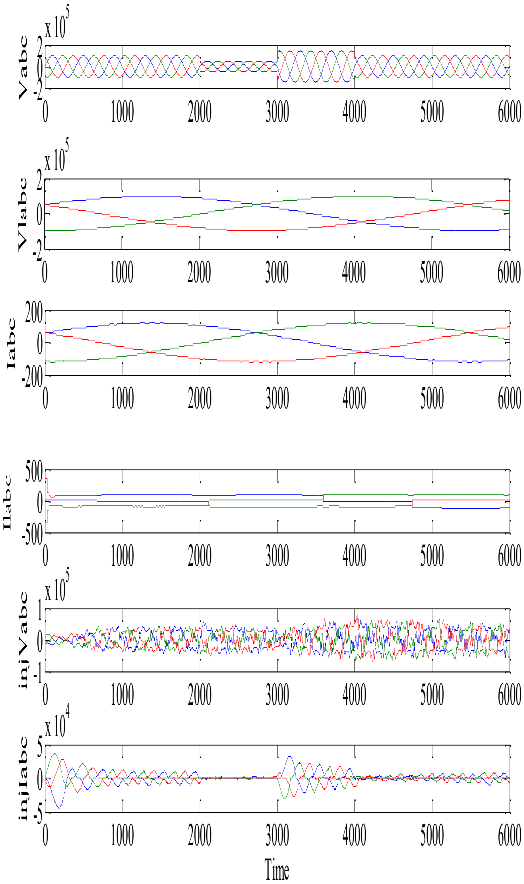

Fig.14 Voltage and Current Waveform of Load Side, Source Side and Injected Side with Fuzzy Logic controller

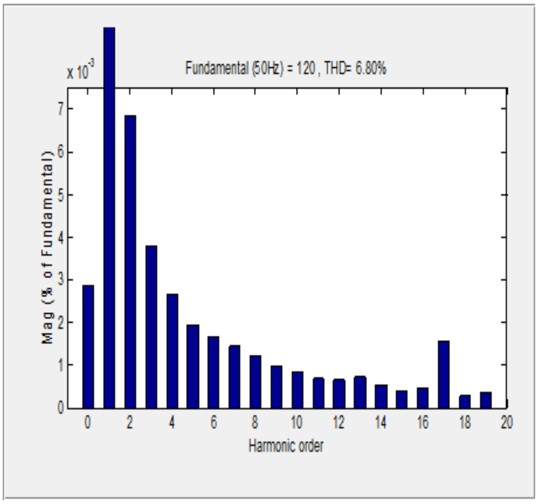

Fig.13 THD of Source Current with PI Controller

With fuzzy UPFC

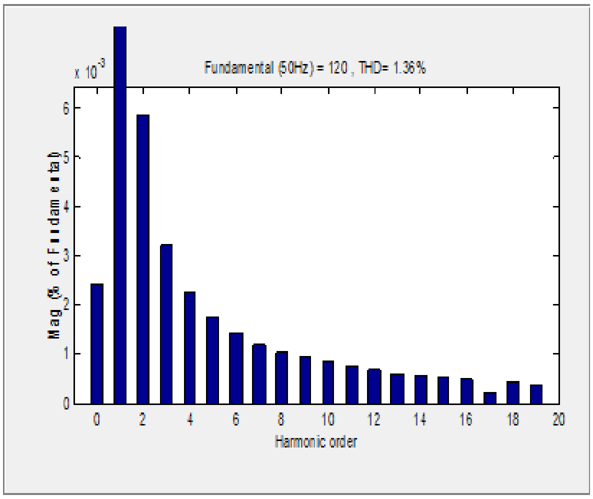

Fig.15 THD of Source Current with Fuzzy Logic controller

5. CONCLUSION

This paper improved that both Voltage and Current quality in a Grid connected DFIG based wind power system. The PQ problems -voltage sag and current harmonics are simulated using MATLAB in a grid connected wind power system. The fuzzy controlled UPQC is implemented for PQ enhancement to diminish both voltage sag and current harmonics and the simulation results are also compared with conventional PI controller. From the simulation results, the PI controlled UPQC completely mitigates voltage sag but the load current harmonics obtained is not within the acceptable limits. The proposed Fuzzy Logic Controlled UPQC completely mitigates voltage sag and provide improve quality of voltage profile. In addition, the source current harmonics are mitigated in a better-quality way by keeping THD level of source current within acceptable limits as per IEE norms. Thus the proposed Fuzzy controlled UPQC is successfully proven as an efficient device through its excellent Performance for improving PQ in a grid connected power system.

Parameters Values used in Simulation Model

Injection Transformer Turns Ratio=1:1
Shunt APF Filter Inductance L = 3mH
Filter Capacitance C =10 F
DC Link Capacitor = 3000 F
Inverter
IGBT based, 3 Arms, 6 Pulse, Carrier Frequency = 10000 Hz
DFIG
1,5*6 =9MW, 575V

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