Fuzzy Logic Controller Based STATCOM for Grid Connected Wind Turbine System

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Abstract- The use of renewable power sources, like wind power, has been increased recently due to climatic changes caused by fossil fuels and fast depletion of fossil fuels. This has lead to the tremendous increase in the interconnection of wind turbines to power system grid. This interconnection on a large number in to grid causes problems such as power quality, maintaining system voltage, reactive power compensation, control of grid frequency and aspects of power system grid stability. In this proposed scheme, a fuzzy logic controller (FLC) is employed for a STATCOM to improve the power quality. The proposed control scheme supplies the required reactive power to the system and thus relieves the source, leading to unity power factor (UPF) at the source and also it injects currents to reduce total harmonic distortion (THD) to satisfy IEC standard. The proposed control scheme of the STATCOM for the grid connected wind turbine system is modeled and simulated using MATLAB/SIMULINK. For extracting the reference currents, a modified synchronous reference frame theory (MSRFT) based control algorithm is employed. The current harmonics injected in to the grid shall also affect the voltage quality at the point of common coupling. The synchronous reference frame theory (SRFT) based control algorithm extracts reference currents for grid synchronisation by employing a 3-Φ phase locked loop (PLL). The voltages fed to the 3-Φ PLL shall define the speed of the reference frame and it is going to vary as the PCC voltages are influenced by harmonics injected. This shall have a great influence on the grid synchronisation and the required results shall not be obtained. To eliminate the above said problems, the MSRFT shall be employed here, where the PLL is not utilised for grid synchronisation. To emphasize the advantages of the MSRFT method, a comparative analysis is also performed with SRFT based control algorithm and the simulation results have been presented. To determine the effectiveness of the proposed FLC, a comparative analysis is also performed with a PI controller and the simulation results have been presented.

Keywords- Wind Turbine (WT); Static Synchronous Compensator (STATCOM); Bang-Bang Current Control (BBCC); Fuzzy Logic Controller (FLC); Modified Synchronous Reference Frame Theory (MSRFT).

1. Introduction

Concern for increasing price of energy, climatic changes due to the use of fossil fuels, rapid decline of fossil fuel reserves and the need to decrease green house gas emissions are some of the factors that encouraged the rapid growth of the sustainable energy sector. Among all the sustainable power sources, wind energy sector has undergone enormous progress recently due to its clean and economical nature [1, 2, 3]. During the past few years, wind turbines (WT) installations for both standalone and grid connected has been increased to a great extent in the entire world. For example, in European Union (EU) 12,800 MW of wind turbines were installed during 2015, an increase of 6.3 % when compared to 2014. Wind power installations alone contributed for 44.2 % of total power installations in EU in 2015. Wind energy installations are present in more than 80 countries globally and 28 countries are having more than 1 GW installation capacity [4, 5].

The Power Quality (PQ) of the power system grid will be influenced on incorporating Wind Turbine System (WTS) in to the power system grid. The WTS is most commonly equipped with Induction Generator (IG) for generating electric power. The use of IG has merits like: economical, robustness, compact size, brushless construction (in squirrel cage arrangement), almost maintenance free, not necessary to have DC source for magnetization and inbuilt protection for overloads and short circuit. On the other hand, an IG takes reactive current for producing the necessary magnetic flux and thus the source is forced to supply the reactive power required for the IG [6].

During the last decade, the grid integration of wind turbines has been increasing tremendously, leading to change of role of WTS from a minor power source to major power source, like thermal power stations, in the grid. Utilities consider the wind energy as the risky source in the aspects of the PQ and the PQ is considered as the complex issue in the grid connected WTS. The PQ of the WTS must be assessed on the basis of international standards and guidelines and it was initiated by International Electrotechnical Commission (IEC) in 1995. IEC issued a draft IEC-61400-21 standard for certifying the PQ requirements for grid connected WTS in the year 1998. Later, IEC published the first edition of IEC-61400-21standard in the year 2001 and then the second edition in the year 2008. Recently, measurement of the sub grouped harmonics, interharmonics and higher frequency harmonics is treated in IEC 61000-4-7 [7, 8].

Induction generator based isolated wind energy generation system studies is available in literature. E. Mulzadi and T. Lipo in [9] have proposed series compensated PWM inverter with a battery for regulating PQ aspects like voltage and frequency for isolated operation of IG. Dynamics and stability analysis and control of WTS using an IG have been reported in [10], [11]. Control schemes for voltage and frequency control of isolated WTS based on IG has been reported in [12] and [13]. Recently, the interest in grid integrated WTS studies has been increased. The effects of penetration of wind power in to the power system grid are no longer negligible as more number of wind generators is being integrated in to the grid. The study of the effects of grid integration of wind energy is available in the literature. R. Fadaeinedjad, G. Moschopoulos and M. Moallem in [14] have investigated the mitigation of voltage fluctuations caused by turbulence using STATCOM. The effects of yaw error and turbulence on the power and voltage variations at Point of Common Coupling (PCC) were studied. The system is modeled to show the effects of wind velocity variations and turbulence on the generated power and system voltage. However, this paper does not discuss the impact of the presence of non linear load in the grid on the power quality aspects. Guizhen Tian, Shengtie Wang and Guangchen Liu in [15] has utilized a STATCOM to mitigate the voltage fluctuations and to improve fault ride through capability of grid connected wind farm with fixed speed IG. The control strategy employed here is the conventional vector control with the negative sequence voltage feed-forward control, where the conventional vector control shall take care of PCC voltage and DC link voltage of STATCOM and the other control effectively suppressed over current of STATCOM. A capacitor bank is connected at the terminal of each wind turbine in addition to STATCOM to take care of reactive power requirements. The simulation study does not indicate whether there is any burden on the grid to provide reactive power. At present, the presence of non linear load in the grid is prevalent, but this study does not take in to account this aspect and the consequent power quality issues. V.Suresh Kumar, et.al in [16] have utilized a STATCOM to overcome the PQ problems like voltage fluctuations and harmonics, but here the authors did not provide many details about control strategy employed. In this paper a power electronic converter is employed for tracking maximum power at the available wind speed and the use of this power electronic converter caused the injection of harmonics in to the grid. J. Castaneda, et.al in [17] employed a STATCOM with a Battery Energy Storage System (BESS) to overcome the PQ problems with the integration of wind farm with abundant wind power to the existing grid in the Southern California Edison power system. The proposed STATCOM-BESS system prevents the power system from collapsing under critical contingencies and provides voltage support. The BESS contributed to minimize wind power variations and to control wind farm output with in a preset values. In this paper, BESS is operated independently and it is not integrated with STATCOM and so control logic is independent for both BESS and STATCOM. Generally the STATCOM and BESS are integrated and accordingly the control strategy employed is not suitable and it should be changed. H.T. Wu and Y. H. Liu in [18] employed the STATCOM with SPWM technique having decoupled control to compensate the reactive power of wind farm. The controller in this paper is based on partial linearization and the control parameters are modulation ratio (M) and phase difference angle (δ) to obtain improved STATCOM dynamic response and flexible reactive power control. The controllable input is restricted in a small margin around zero to guarantee the linearization accuracy and this constraint makes the dc voltage to be controlled slowly, consequently larger dc capacitance for dc voltage stiffness. From the waveforms, it is not clear whether the source is completely relieved from supplying the reactive power and the study regarding the effect of harmonics in the system was not performed. A. Arulampalam, et.al in [19] have proposed a STATCOM-BESS to address two problems: PQ and stability. Two control strategies have been proposed, one for the PQ improvement by reducing the voltage fluctuations and the other for improving the WT stability. In this paper, STATCOM alone is not taking care of the required reactive power and additionally a capacitor is connected to the induction generator. In this paper, the study is limited only to mitigate voltage fluctuations and the other power quality problems has not been paid due attention. The study in the paper does not mention details regarding the power factor at source and the presence of nonlinear load in the grid, which is most prevalent, has not been considered for study. Wei Qiao and Ronald G. Harley in [20] have employed a STATCOM to minimize voltage fluctuations at Point of Common Coupling (PCC) and voltage instability during grid faults. Two different control schemes have been proposed; first one is based on conventional PI control and the other is a nonlinear control scheme based on input-output feedback linearization (IOL). Both the controllers performed equally well in flicker mitigation and transient PCC voltage regulation but IOL is better in transient dc-link voltage regulation. This paper concentrated on mitigation of voltage fluctuations at PCC and enhancing the fault ride-through capability of the WT and this study has not provided any information about power factor at source side of the grid. At present, the presence of non linear load in the grid is prevalent, but this study does not take in to account this aspect and the consequent power quality issues. From the above discussion, it is clear that, there has been paid little attention towards the presence of non linear load in the grid and the consequent power quality issues and the mitigation techniques. However, achieving the required power quality norms and reactive power compensation of the grid connected WTS consisting of nonlinear load using Fuzzy Logic Controller (FLC) based STATCOM by employing Modified Synchronous Reference Frame Theory (MSRFT) for extracting the reference currents for grid synchronization has received a very little research attention.

In this paper, WTS with induction generator, connected to the grid consisting of the nonlinear load is considered for detailed study of the associated PQ problems and reactive power compensation. The current harmonics injected by non linear load in to the grid shall also affect the voltage quality at the point of common coupling (PCC). The Synchronous Reference Frame Theory (SRFT) based control algorithm extracts reference currents for grid synchronization by employing a 3-Φ phase locked loop (PLL). The voltages fed to the three phase PLL shall define the speed of the reference frame and it is going to vary as the PCC voltages are influenced by harmonics injected. This shall have a great influence on the grid synchronization and the required results shall not be obtained. To eliminate the above said problems, the MSRFT shall be employed here, where the 3- Φ PLL is not utilized for grid synchronization. To determine the effectiveness of the proposed fuzzy logic controller, a comparative analysis is also performed with a PI controller. The reference currents are compared with the actual currents and the error is fed to the Bang-Bang Current Controller (BBCC), which generates the switching signals to the STATCOM. The proposed controller provides reactive power to non-linear load and induction generator and thus maintains UPF at the source side and also reduces THD in the system to the prescribed limits.

2. Configuration of Grid Connected Wind Turbine System

The proposed grid connected WTS for power quality enhancement is shown in Fig. 1. The system consists of induction generator based wind turbine, non linear load and STATCOM, all connected to grid at PCC. The STATCOM compensator's output is changed as per the control strategy, so as to maintain the power quality norms in the grid system. The details of the proposed control scheme are shown in Fig. 2. The proposed control scheme shall take grid voltages, V_{sa}, V_{sb}, and V_{sc}, source currents, I_{sa}, I_{sb}, and I_{sc}, load currents, I_{La}, I_{Lb}, and I_{Lc} and DC link capacitor actual voltage value, V_{dc} and DC link capacitor reference voltage value, V_{dcref} as inputs and the controller shall give desired switching pulses for the STATCOM so as to inject the current such that the source current is harmonic free and also cancels the reactive current part of the load and induction generator, thus the STATCOM with the proposed control scheme improves the power factor and the power quality of the grid connected WTS.

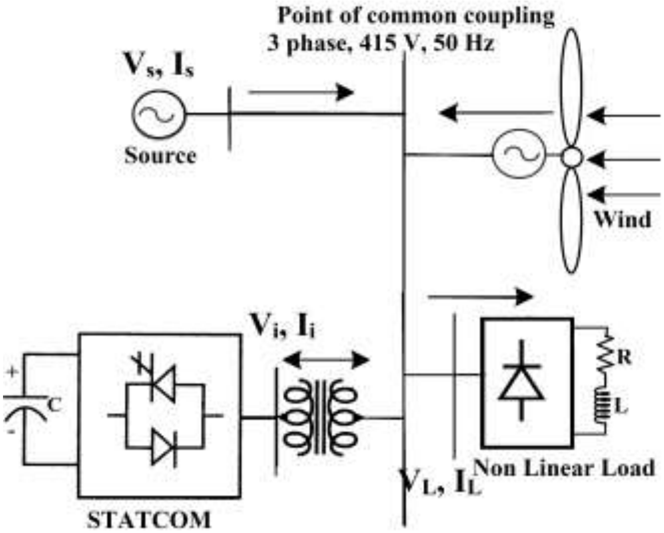

Fig. 1. Grid connected wind turbine system

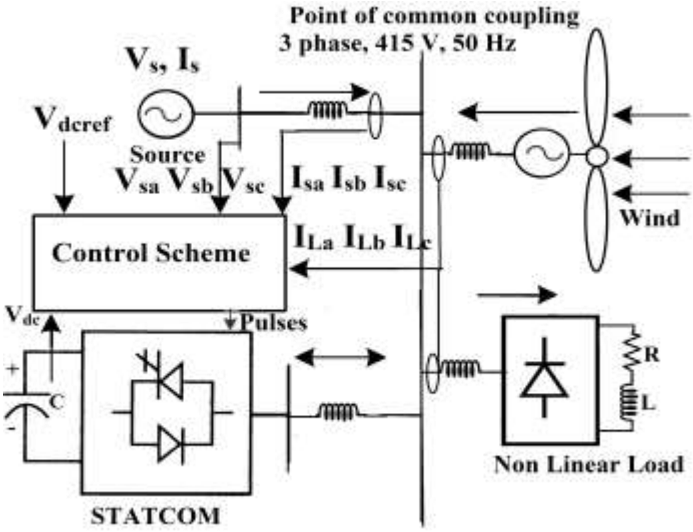

Fig. 2. Control scheme details

2.1 Wind Turbine System

The Wind turbine is coupled to generator so as to convert the kinetic energy of the wind to rotating torque for the generator. Normally 3-Φ alternators, PMSG and IGs are used as generators in WTS. PMSG and squirrel cage IG are popular because of reliability and economy. In the proposed grid connected system, the WT used is constant speed with pitch control. The squirrel cage induction generator is used in the proposed system because of economical, simple and rugged construction, no need of DC excitation, and has natural protection for short circuit [21, 22]. The total power available in the wind is [23]

$$P_w = \frac{1}{2}\rho A v_w^3 \quad (1)$$

Where A is area swept by WT blade in m^2, ρ is air density in kg/m^3, v_w is the wind speed in m/s. WT extracts a portion of power in wind, as given by

$$P_m = C_p P_w \tag{2}$$

Where C_p is the power coefficient of WT. The electrical power output is then [24]

$$P_e = C_p \eta_m \eta_g P_w \tag{3}$$

Where η_m is the mechanical system efficiency and η_g is the efficiency of the generator.

2.2 Static Synchronous Compensator (STATCOM)

In recent times, a Voltage Source Inverter (VSI) based advanced static var compensators, also known as STATCOM, is utilized for reactive power control [25, 26]. The STATCOM is also a VSI, but connected to a grid system rather than to a passive load. The STATCOM requires a DC source and it is being served by a capacitor. As the capacitor can store only a negligible charge, STATCOM can supply a very negligible active power. Just like rotating synchronous machines, the reactive power transfer between the STATCOM and the grid shall be managed by changing the magnitude of the output voltage of STATCOM. The magnitude and phase angle of the STATCOM are controlled to achieve the desired reactive power control. Depending on the voltage magnitude of STATCOM, it behaves like an inductor or capacitor. If the voltage value of STATCOM is made higher than the grid voltage, it behaves as a capacitor. For the STATCOM output voltage magnitude lesser than grid voltage, it behaves like an inductor. Therefore by continuous voltage variation of STATCOM, the reactive power output of STATCOM shall be varied continuously [25, 27, 28]. In [29, 30], the benefits of STATCOM over other devices for reactive power compensation has been discussed.

3. Control Scheme

In the proposed control scheme, the reference currents for the purpose of grid synchronization are obtained by using the Modified Synchronous Reference Frame Theory (MSRFT). In the MSRFT no three phase PLL is employed for achieving the grid synchronization, whereas SRFT employs a three phase PLL for the purpose of accomplishing the grid synchronization. The current harmonics injected by non linear load in to the grid shall also affect the voltage quality at the point of common coupling (PCC). Hence the polluted grid voltages fed to three phase PLL shall not give the proper reference currents for grid synchronization in SRFT based control scheme. The voltages fed to the three phase PLL shall define the speed of the reference frame and it is not going to be constant in SRFT based control scheme as the PCC voltages are polluted by injected harmonics. This shall have a great influence on the grid synchronization and the desired results shall not be obtained. To eliminate the above said problems, the MSRFT shall be employed here, where the 3- Φ PLL is not utilized for grid synchronization. First the SRFT control scheme and then MSRFT control scheme is explained here in detail.

3.1 Synchronous Reference Frame Theory (SRFT)

In order to achieve the desired power quality norms in the grid connected WTS, the reference currents for achieving grid synchronization are extracted by employing SRFT based control algorithm, which is simple and easy to implement. The details of the SRFT based control strategy is shown in Fig. 3. SRFT is based on the transformation of currents in synchronously rotating d–q frame. It employs the PLL block to evaluate transformation angle, θ, and this angle is used to convert currents from abc to dq0 reference frame. The three phase instantaneous voltages at PCC, v_{sa}, v_{sb}, and v_{sc}, the load currents, i_{La}, i_{Lb} and i_{Lc} and the DC link capacitor voltage, v_{dc}, are sensed and given as inputs to the controller. Voltage signals at PCC are processed by a three phase PLL to generate unit voltage templates (sine and cosine signals). The three phase load currents are transformed in to dq0 reference frame using park's transformation as follows [31, 32].

$$\begin{pmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta+\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) & \frac{1}{2} \end{pmatrix} \begin{pmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{pmatrix} \tag{4}$$

For the purpose of synchronizing with grid voltages, a three phase PLL is used and it is fed with PCC voltages as input. The transformed load current components are passed through a low pass filter to extract DC components and the other components of currents are separated so that they do not appear in the obtained reference currents from the controller.

$$i_{Ld} = i_{dDC} + i_{dAC} \tag{5}$$

$$i_{Lq} = i_{qDC} + i_{qAC} \tag{6}$$

The control scheme shall take care to maintain unity power factor (UPF) by making the source to supply the DC component, i_{dDC}, along with current to maintain stiff DC bus voltage and also to meet the losses of the STATCOM. The output of the PI controller gives the current, i_{loss}, as shown below:

$$i_{loss}(n) = i_{loss}(n-1) + K_{pd}\{v_{de}(n) - v_{de}(n-1)\} + K_{id} v_{de}(n) \tag{7}$$

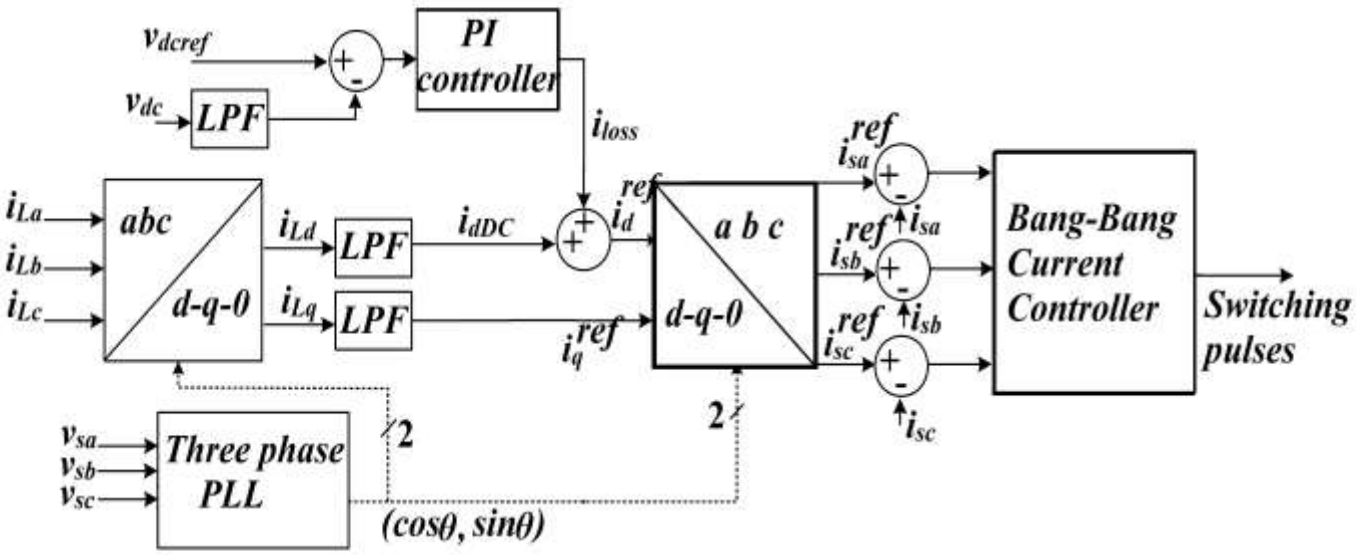

Fig. 3. Block diagram of the SRFT based control system

Where $v_{de}(n) = v_{dcref}(n) - v_{dc}(n)$ is the error between reference and actual DC link capacitor voltage at n[th] sampling instant and K_{pd} and K_{id} are the proportional and integral gain constants of the PI controller. The output of PI controller accounts for the losses of STATCOM and this component is added to the i_{dDC} for power factor correction. The obtained reference currents shall be in dq0 frame and by applying reverse Park's transformation, the obtained dq0 frame reference currents are transformed to abc frame.

$$\begin{pmatrix} i_{sa}^{ref} \\ i_{sb}^{ref} \\ i_{sc}^{ref} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{pmatrix} \begin{pmatrix} i_{d}^{ref} \\ i_{q}^{ref} \\ i_{0}^{ref} \end{pmatrix} \quad (8)$$

3.2 Bang-Bang Current Controller (BBCC)

In the Bang-Bang Current Controller (BBCC), hysteresis comparator controls the steady-state error by varying the hysteresis bandwidth (HB). It is also known as hysteresis current controller. In this paper, a two level hysteresis comparator namely, lower hysteresis band (LHB) and upper hysteresis band (UHB) is employed to determine the steady-state error. The actual currents are measured by sensors and the reference currents are calculated using Eq. (8). On comparing actual and reference currents, a current error is obtained, which is fed to a BBCC. The BBCC shall generate switching signals for IGBTs of STATCOM so as to inject currents to force the actual current within the hysteresis region of the reference current so as to obtain UPF at source and THD as per norms [33, 34]. Figure 4 shows the method for obtaining switching signals for IGBTs of STATCOM. Switches are switched ON and OFF randomly in order to track the reference current and maintain the current error within the pre-assigned bandwidth.

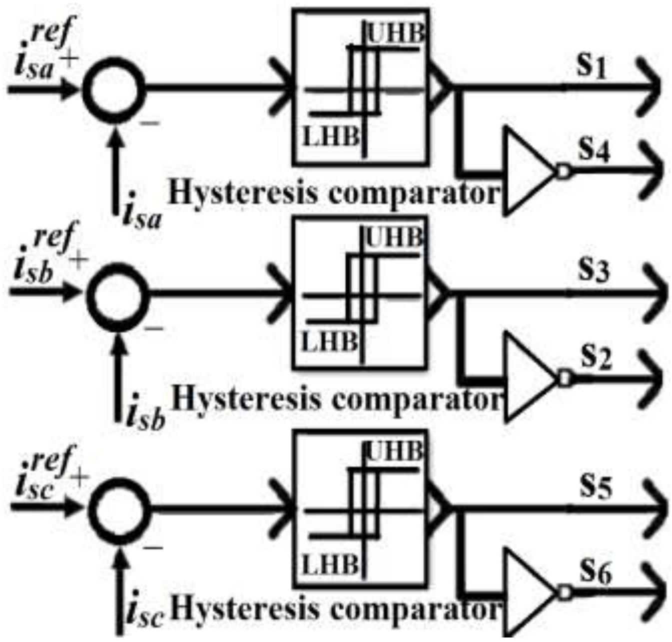

Fig. 4. BBCC for generation of switching signals

3.3 Modified Synchronous Reference Frame Theory(MSRFT)

This method is similar to SRFT method but the transformation angle, θ, required for synchronization, is obtained from grid voltages by employing a simplified unit vector generator rather than employing a three phase PLL. The details of obtaining transformation angle, θ, in MSRFT based control scheme is shown in Fig. 5. By eliminating 3-Φ PLL, many problems associated with PLL synchronization are eliminated and absolutely frequency independence is achieved. If the grid voltages are balanced and harmonics free, then the transformation angle, θ, is uniformly increasing function with time. This transformation angle is sensitive to voltage harmonics and unbalance; therefore dθ/dt may not be constant. As PLL is avoided, a wide range of operating frequency is obtained. The speed of the reference frame depends on the instantaneous grid voltages fed to PLL.

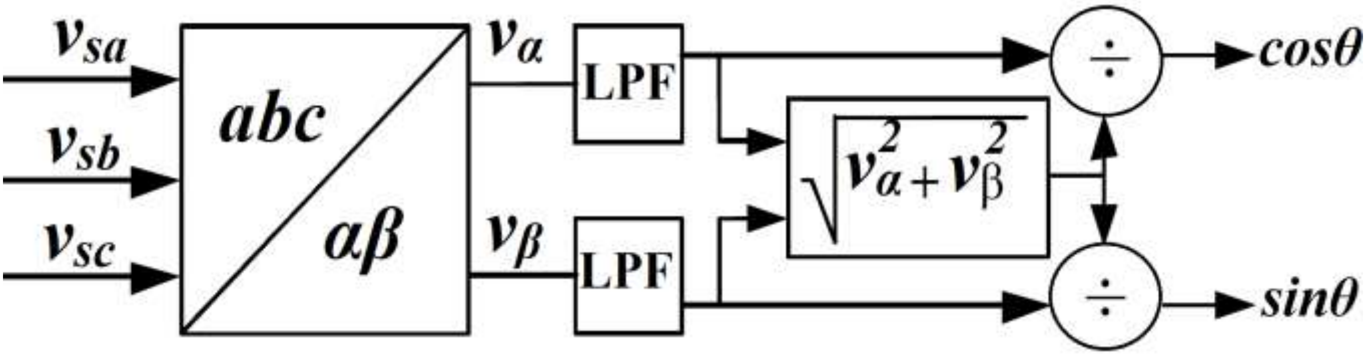

Fig. 5. Block diagram for transformation angle generation in MSRFT

As the grid voltages are affected by the harmonics injected, the reference frame's speed is not going to be constant anymore and hence the performance of the SRFT based control strategy shall not be the desired one [35, 36]. The details of obtaining unit vectors (*cos θ, sin θ*) for synchronization is presented below.

The three phase grid voltages are first sensed and transformed to α-β coordinate system by using Clarke transformation.

$$\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{pmatrix} \tag{9}$$

These source voltages in the α-β coordinate system are filtered using appropriate low pass filter to eliminate the harmonics in the voltages. Though α-β voltages are used for calculating the transformation angle, θ, low pass filters (LPF) are still employed to reduce the harmonics in the PCC voltages. This LPF is desirable because the method becomes less affected by harmonics in the grid voltages. The resulting voltages after Clarke transformation are as follows:

$$v_\alpha = \frac{\sqrt{3}}{2} v_m \cos\theta \tag{10}$$

$$v_\beta = \frac{\sqrt{3}}{2} v_m \sin\theta \tag{11}$$

The space vector in α-β coordinate system can be expressed as

$$V_{\alpha\beta} = v_\alpha + j v_\beta \tag{12}$$

Now, we can express unit vectors (*cos θ, sin θ*) needed for grid synchronisation in MSRFT based control scheme as follows:

$$\frac{v_\alpha}{\sqrt{v_\alpha^{\,2} + v_\beta^{\,2}}} = \frac{\frac{\sqrt{3}}{2} v_m \cos\theta}{\frac{\sqrt{3}}{2} v_m} = \cos\theta \tag{13}$$

$$\frac{v_\beta}{\sqrt{v_\alpha^{\,2} + v_\beta^{\,2}}} = \frac{\frac{\sqrt{3}}{2} v_m \sin\theta}{\frac{\sqrt{3}}{2} v_m} = \sin\theta \tag{14}$$

From the above analysis, it is clear that the tranformation angle, θ, is computed from the grid voltages by employing a simplified unit vector generator rather than employing a three phase PLL and thus enablies it to be frequency independent. The LPFs shown in Fig. 5 are employed to decrease the voltage harmonics. Using the angle, θ, the reference *d*, *q* components of currents are obtained. By applying reverse Park's transformation, the 3-Φ reference supply currents shall be obtained. These reference currents are compared with the sensed supply currents (i_{sa}, i_{sb}, and i_{sc}) to estimate the 3-Φ current error components. The flowchart that explains the various steps of analysis involved in the MSRFT is shown in Fig. 6.

3.4 Fuzzy Logic Controller (FLC)

Recently, a lot of interest has been shown in the research of applications of FLC. FLC is an expert system, which tries to implement human knowledge in the form of if-then rules. In the conventional control systems, like PI and PID controllers, rigorous mathematics is needed to model the system and if the mathematical model is not known, then the conventional controllers cannot be designed. The structure of FLC consists of four parts, namely, Fuzzification, knowledge base, inference and defuzzification.

In this paper, the PI controller shown in Fig. 3 is now replaced with a FLC, as shown in Fig. 7. The inputs to the FLC are error and change in error and the output of the FLC is i_{loss}. The input and output variables are fuzzified by using the seven fuzzy sets: NL (negative large), NME (negative medium), NS (negative small), Z (zero), PS (positive small), PME (positive medium), and PL (positive large). The normalized membership functions for input and output variables are shown in Fig. 8. The knowledge is represented in the form of rules and the rules employed are summarised in Table 1. Inference is done using Mamdani's min operator and finally, the output is converted to crisp set by defuzzification using centroid method.

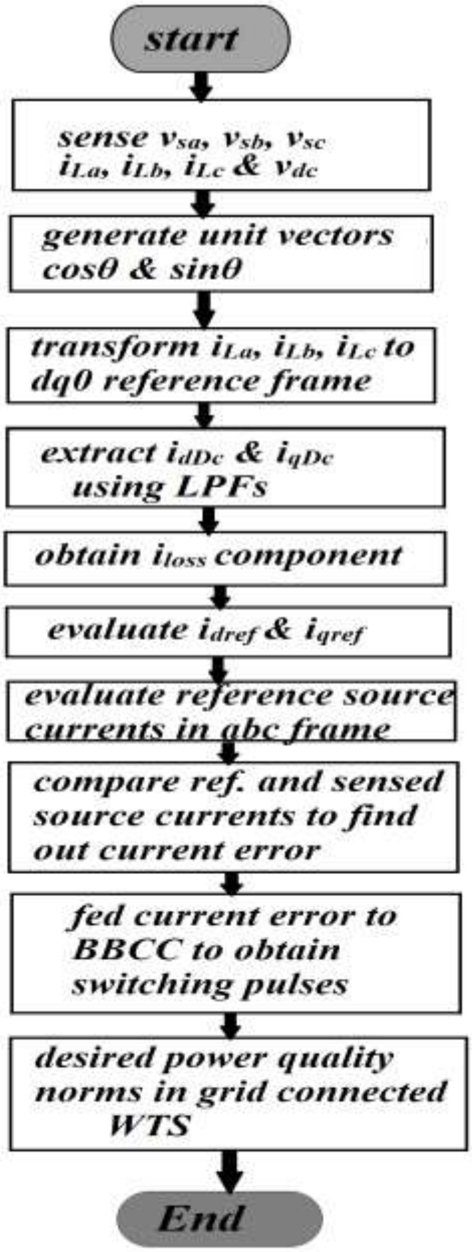

Fig. 6. Flow chart showing various steps of analysis of MSRFT control scheme

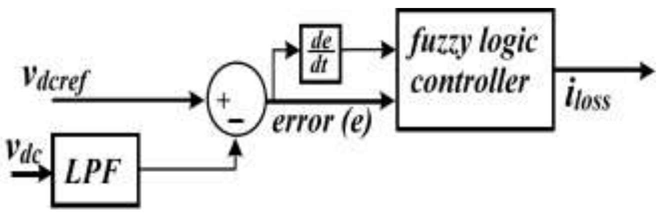

Fig. 7. Block diagram of FLC

4. Results and Discussion

The system considered for power quality improvement, as shown in Fig. 1, is simulated using MATLAB/SIMULINK. The power quality of the system, as shown in Fig. 1, is mainly affected by the nonlinear load and wind turbine. In this paper, to have the comparative analysis

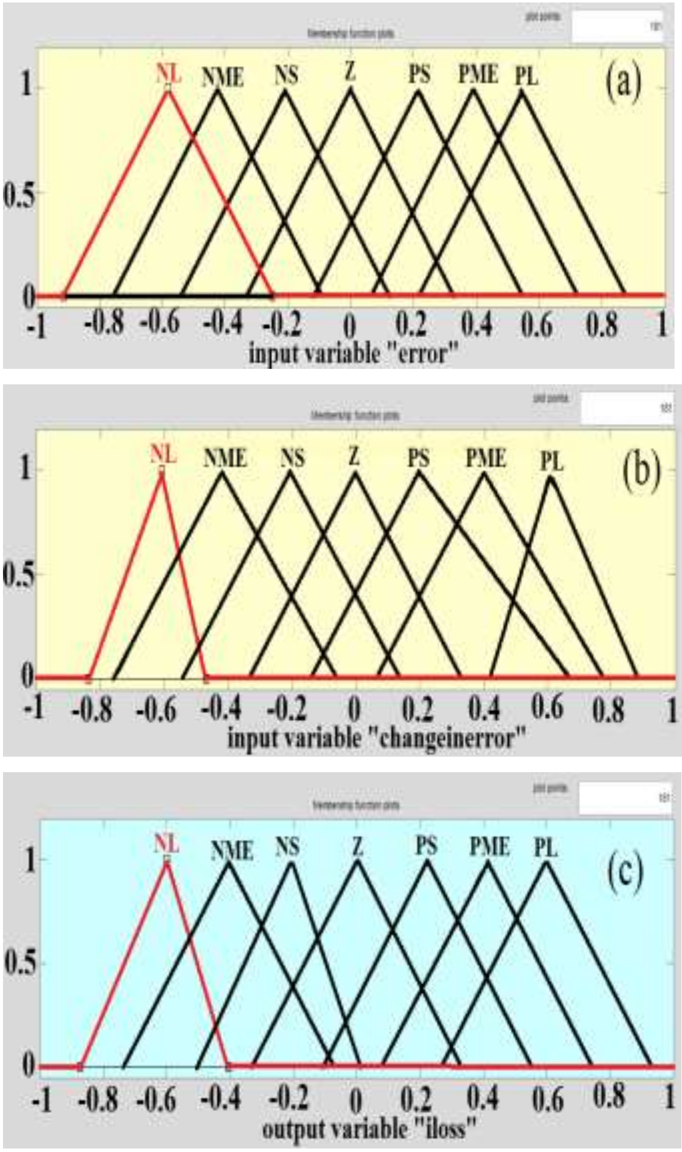

Fig. 8. Membership functions (a) error (b) change in error (c) output

of the performance of the proposed FLC based STATCOM with MSRFT based control scheme, the proposed system is also simulated without STATCOM and then with PI controller STATCOM with MSRFT based control scheme. Finally, the proposed system is also simulated with SRFT based control scheme in order to have the comparative analysis with MSRFT.

4.1 System performance without STATCOM and its controller

The waveforms related to the simulation of the system without STATCOM are shown in Fig. 9. Due to nonlinear load, the load current is not sinusoidal, as it is clear from Fig. 9 (a) and this load current cause the source current distortions, as shown in Fig. 9 (b). The THD of the source current is 26.12 %, as shown in Fig. 10 and it is highly undesirable. Both nonlinear RL load and induction generator consume reactive power causing power factor at the source lagging, as it is clear from Fig. 11.

Table 1. Rule base

e / ce	NL	NME	NS	Z	PS	PME	PL
NL	NL	NL	NL	NL	NME	NS	Z
NME	NL	NL	NL	NME	NS	Z	PS
NS	NL	NL	NME	NS	Z	PS	PME
Z	NL	NME	NS	Z	PS	PME	PL
PS	NME	NS	Z	PS	PME	PL	PL
PME	NS	Z	PS	PME	PL	PL	PL
PL	Z	PS	PME	PL	PL	PL	PL

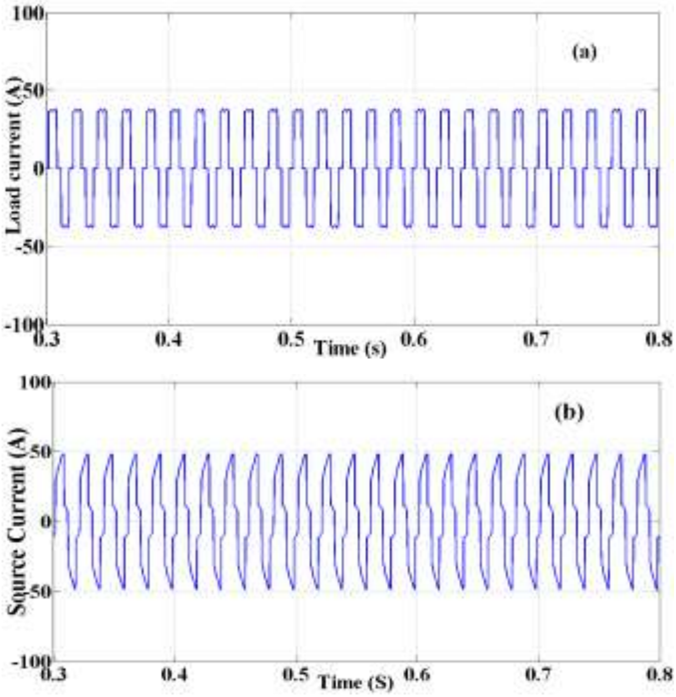

Fig. 9. (a) Load Current (b) Source Current, Without STATCOM.

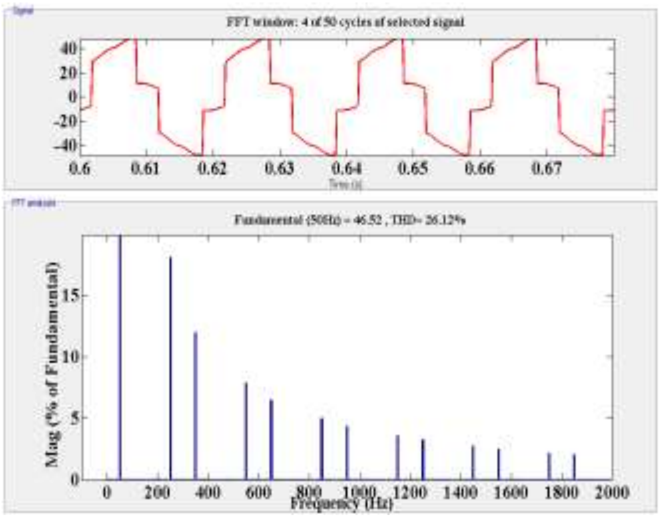

Fig. 10. FFT analysis of Source current

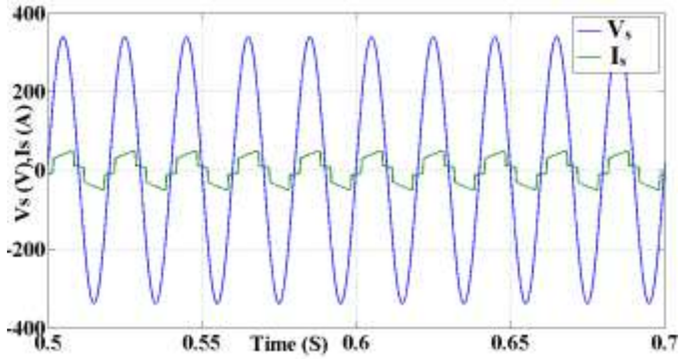

Fig. 11. Supply voltage & supply current, without STATCOM

4.2 System performance with STATCOM and its SRFT based controller

The same system is simulated with the STATCOM and its SRFT based controller. Due to non-linear load, the load current is highly distorted, as shown in Fig. 9 (a). Because of this load, harmonics are injected to source current also, but the STATCOM injected current shall cancel out the harmonics, thus causing the source current to be sinusoidal, as shown in Fig. 12. Figure 13 shows the THD of source current as 12.84 %, which is not acceptable as per the standards. Figure 14 shows the waveforms of source voltage and source current and from this waveform it can be seen that that the power factor is varying and it is not maintained unity. The above problems are due to the use of three phase PLL, which is fed with PCC voltages that are polluted due to harmonics injected. Due to the synchronisation problems, the results obtained with SRFT controller are not satisfactory and thus it is not acceptable as per the norms.

4.3 System performance with STATCOM and its MSRFT with PI controller

The same system is simulated with the STATCOM and its MSRFT with PI controller. Due to non-linear load, the load current is highly distorted, as shown in Fig. 9 (a). Because of this load, harmonics are injected to source current also, but the STATCOM injected current shall cancel out the harmonics, thus causing the source current to be sinusoidal,

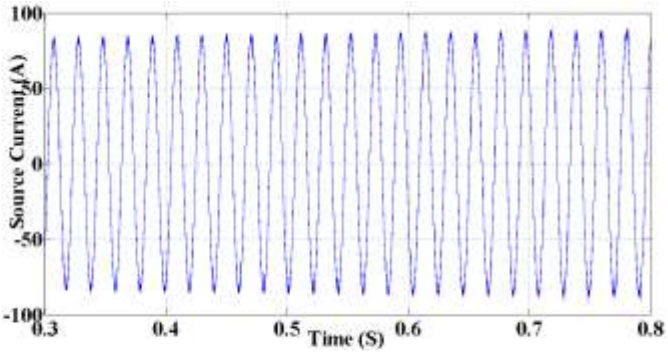

Fig. 12. Source current with STATCOM and its SRFT based controller

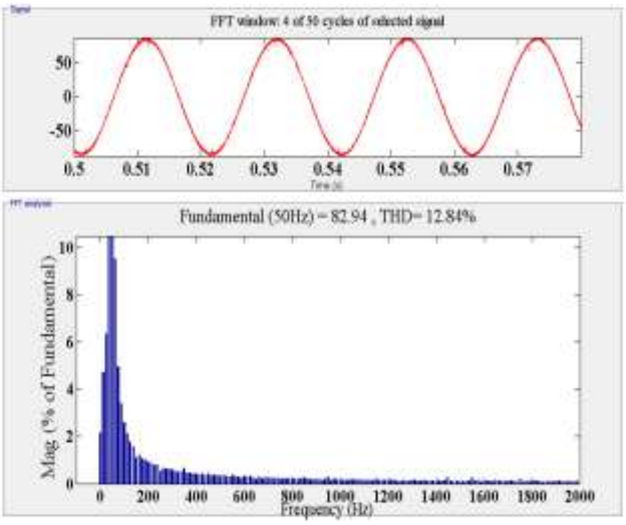

Fig. 13. FFT analysis of Source current with STATCOM and its SRFT controller

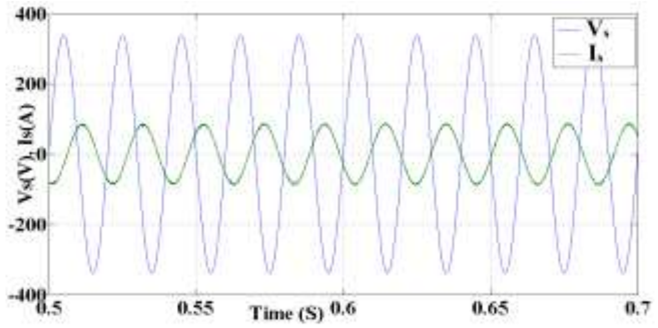

Fig. 14. Supply voltage & supply current, with STATCOM and SRFT controller

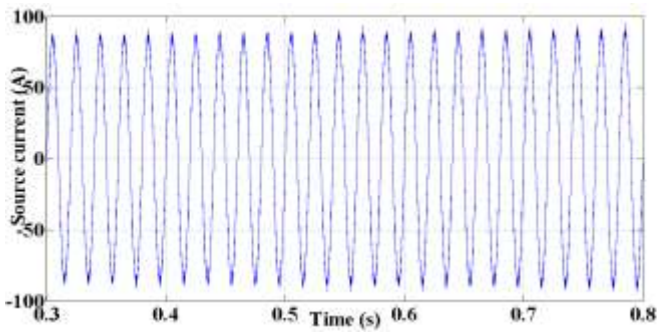

Fig. 15. Source current with STATCOM and its MSRFT with PI controller

as shown in Fig. 15. Figure 16 shows the THD of source current as 2.27%, which is acceptable as per the standards. Figure 17 shows the waveforms of source voltage and source current and from this waveform it can be seen that that the power factor is maintained unity. STATCOM is supplying the reactive power required, thus maintaining UPF at source side, as it is clear from Fig. 17. The problems that are present in the SRFT have been eliminated in the MSRFT, as the three phase PLL is eliminated for synchronisation.

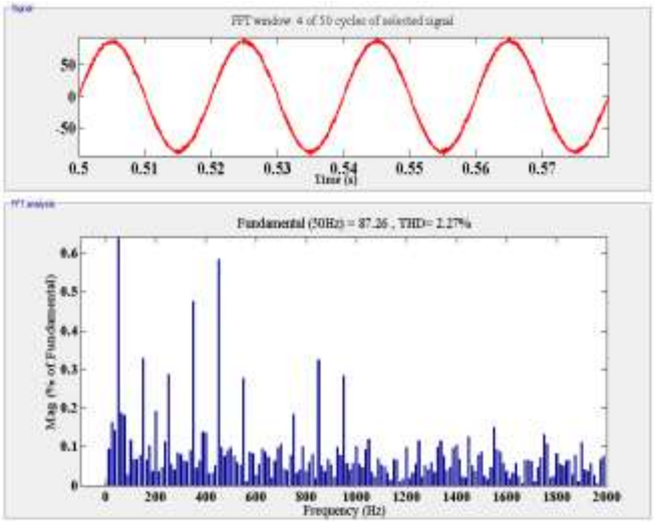

Fig. 16. FFT analysis of Source current with STATCOM and its MSRFT with PI controller

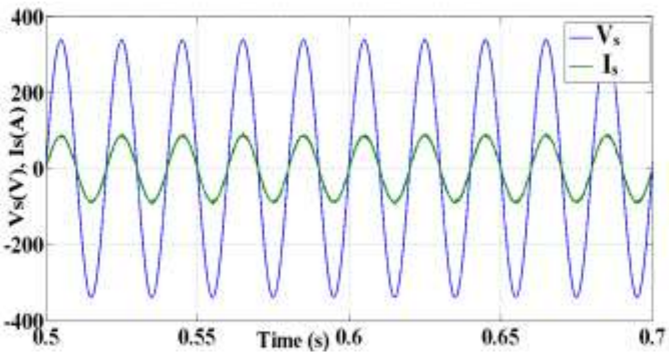

Fig. 17. Supply voltage & supply current, with STATCOM and its MSRFT with PI controller

4.4 System performance with STATCOM and its MSRFT with FLC

The same system is simulated with the STATCOM and its MSRFT with FLC. Due to non-linear load, the load current is highly distorted, as shown in Fig. 9 (a). Because of this load, harmonics are injected to source current also, but the STATCOM injected current shall cancel out the harmonics, thus causing the source current to be sinusoidal, as shown in Fig. 18. Figure 19 shows the THD of source current as 1.81%, which is acceptable as per the standards. Figure 20 shows the waveforms of source voltage and source current and from this waveform it can be seen that that the power factor is maintained unity. It is clear from Fig. 20 that the STATCOM is supplying the required reactive power and thus maintaining UPF at source side.

Table 2. Comparison of performance of the system

S. No	Without STATCOM	With STATCOM and its SRFT controller	With STATCOM and its MSRFT with PI controller	With STATCOM and its MSRFT with FLC
1.	High harmonic content in source and load currents.	Source current harmonics are not effectively compensated.	Source current harmonics are compensated.	Source current harmonics are compensated.
2.	Source current's THD is 26.12 %.	Source current's THD is 12.84 %.	Source current's THD is 2.27 %.	Source current's THD is 1.81 %.
3.	Supply power factor is lagging	Supply power factor is not maintained at UPF and it is changing due to synchronisation problems.	Supply power factor is UPF	Supply power factor is UPF

The use of FLC instead of PI controller has shown to reduce THD value of source current further and thus improving the performance of the system. Table 2 indicates the comparison of the performance of the test system for various cases.

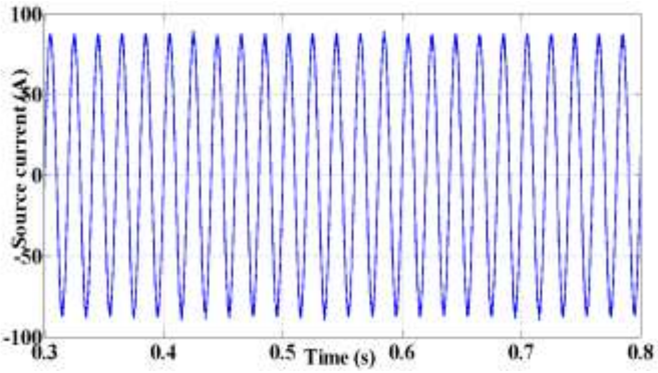

Fig. 18. Source current with STATCOM and its MSRFT with FLC

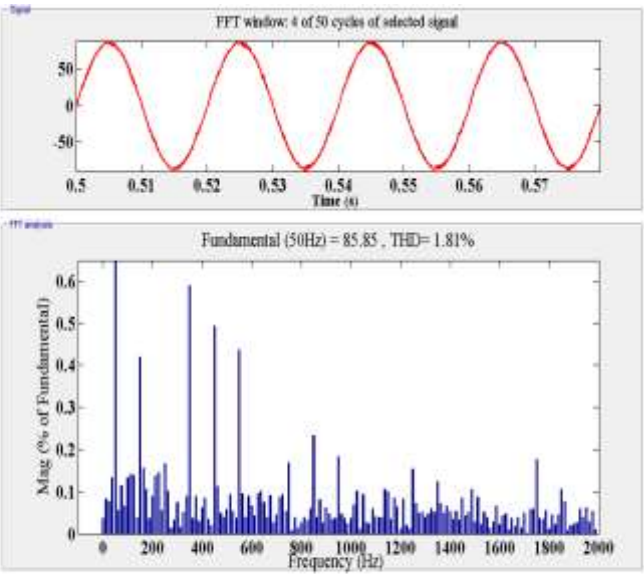

Fig. 19. FFT analysis of Source current with STATCOM and its MSRFT with FLC

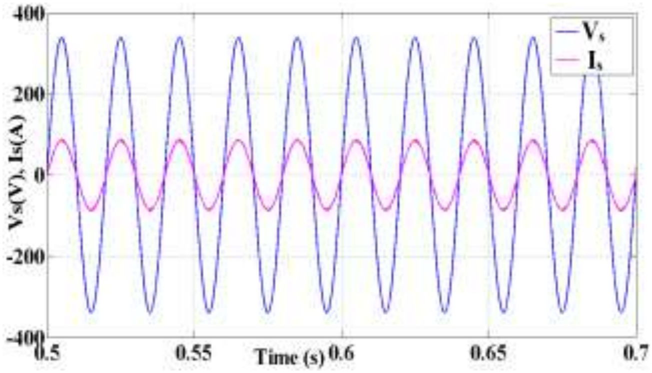

Fig. 20. Supply voltage & supply current, with STATCOM and its MSRFT with FLC

5. Conclusion

The power quality improvement of grid connected WTS using fuzzy logic controller based STATCOM with MSRFT has been presented in this paper. The test system has nonlinear RL load and WTS integrated with induction generator, which causes the potential power quality problems. In the second half of the 20th century, a variety of new electronic devices were introduced, causing distortion in waveforms of the power system. This made the study of the power quality of the power system a very important one. This paper showed that the source current is highly distorted due to the presence of non linear load, as it is clearly indicated by the high value of THD of souce current. Higher THD values of current has negative impacts like increase of the current in power systems, which results in higher temperatures in distribution transformers and neutral conductors. Higher order frequency harmonics results in increased core loss in motors, which results in enormous heating of the motor core. The higher order harmonics can also interfere with communication transmission lines. This clearly indicates the necessity to compensate the harmonics. In this paper, the proposed STATCOM controller has effectively compensated the harmonics injected by non-linear load. The presence of wind generator and inductive load makes the source power factor lagging, which leads to under utilization of the transmission line. This paper demonstrates an effective STATCOM controller to compensate the reactive power and harmonics. The proposed controller shall inject currents in to the grid and reduces the source current THD from 26.12 % to 1.81 %. The controller shall also supply the required reactive power for the load and induction generator and thus helps to maintain UPF at the source. It is clear from the obtained results that the MSRFT based controller STATCOM has shown superior performance over the SRFT controller based STATCOM. The three phase PLL employed in the SRFT control scheme is fed with the grid voltages that are polluted due to the interaction of nonlinear RL load and WTS, causing the synchronisation problems. Thus the SRFT controller based STATCOM does not give the satisfactory results, as it is giving a source current THD of 12.72 % and the power factor at the source is varying and it is not maintained UPF. The MSRFT based STATCOM with FLC has superior performance when compared to MSRFT based STATCOM with PI controller and SRFT based STATCOM as THD values are 1.81%, 2.27% and 12.84% respectively. The grid connected WTS with MSRFT based STATCOM with FLC has shown the outstanding performance by satisfying the power quality norms as per the IEC standard

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