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Fuzzy Based Hex-IPQC Controller for Improving Power Quality in Grid Connected Wind Farms

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Abstract: This research presents the development of Hexagram converter based Interline Power Quality Conditioner (Hex-IPQC) for proposed Hex-IPQC controller transmission lines. To achieve higher level of control, intelligent Fuzzy Logic Control (FLC) is im grid connected wind farms. In this, 3-generators with 13-bus wind farm system have been considered for the implementation of plemented to monitor and control the Hex-IPQC system. The various load disturbances has been taken for the analysis of power quality improvement. Firstly, the simulation study is carried out to validate the experimental results of the proposed WFs. Dynamic simulation results indicates that proposed FLC controller provides right performance for the seamless control, over Hex-IPQC converter when power system instability is detected. The real and reactive power flow through the transmission lines improves and also improves the power quality in the grid tied WFs.

Key words: Fuzzy logic control, hexagram converter, IPQC, wind energy system, power quality

INTRODUCTION

The renewable energy is obtained from various sources like wind, solar and hydro etc. But, Wind Energy System (WES) is commonly used power source for generating renewable electrical power. It provides electrical energy without polluting the environment. One of the foremost problems in wind energy is that irregularity in wind power with wind speed. Therefore, irregular power is to be converted and regulated by power electronic converters and control systems. To minimize the environmental impact on conventional system, wind energy power system integration plays an important role. Compare with conventional wind systems, present technology in wind energy system requires maintaining voltage regulation, stability, power quality problems. In DTC-based WESC is proposed for low power applications which provides better torque control in steady-state and transient operating condition. Similarly, various power quality related issues in wind energy system explained by Qi *et al*. (2008) and Qiao *et al*. (2009). Integrating large wind farms involves complexity in stability and power quality issues.

Flexible AC Transmission System (FACTS) devices has wide development. Since it can control various parameters related to transmission system with a quick response. System oscillations can be controlled within stable limits using FACTS devices and its security improvement is explained by Ambati and Khadkikar (2014), Dizdarevic and Majstrovic (2003), Baxevanos and Labridis (2007), Ji and Egerstedt (2007) and Rohman and John (2006). Improper switching of FACTS controller can creates power quality issues like Total Harmonic Distortion (THD) and Electro-Magnetic Interference (EMI). This will leads to failure of FACTS devices and also electrical equipments at the consumer end. Features such as monitoring, control are explained by Nagata and Sasaki (2002) and Pipattanasomporn *et al*. (2009) and operation functions are incorporated to control and stabilize the complex system using fuzzy inference system investigated by McArthur *et al*. (2007). In hexagram converter has been proposed for the control of three phase motor drive (Wen and Smedley, 2007). Improved power quality results are presented by Slepchenkov *et al*. (2011) and Mohanraj *et al*. (2013) obtained from this multi level based hexagram inverter.

Combined compensators such as unified power flow controller and the interline power flow controller that are based on self commutated, voltage sourced switching converters are turned more versatile. UPQC based power quality improvement and control methods are presented by Accetta *et al*. (2014), Han *et al*. (2014) and Zobaa and Jovanovic (2006). Unlike, the UPFC the IPFC employs at least two VSCs, respectively connected in series with different lines which can address the problem of compensating multiple transmission lines at a given

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substation by Ganguly (2014a) and Khadkikar (2012). Compared with shunt compensators, series compensators are more effective in controlling the transmitted power which is closely related to power system transient stability and investigated by Aryanezhad *et al*. (2013) and Ganguly (2014b). Various studies have been carried out on the development of FACTS controller and its control system briefly explained by Cheng *et al*. (2006), Karanki *et al*. (2011), Santos *et al*. (2014) and Qasim and Khadkikar (2014). However, there is very few open literature on the application of IPQC to the power quality improvement. The various control schemes have been developed for the control of converters in the FACTS controllers investigated by Rangaswami and Sennappan (2013), Karthik and Palanisamy (2014) and Khadem *et al*. (2015). Due to complexity in coordinated control of these FACTS devices with grid parameters, FLC based system provides better responses to the co-ordinate control problems.

MATERIALS AND METHODS

Proposed research: The main focous of this research is to realize new haxagram controller based Interline Power Qulity Conditioner (IPQC) for a 230 kW wind farms. Configuration description of 230 kW wind farm with proposed hexagram IPQC converter is described and illustrated in Fig. 1. The fuzzy logic is used for co-ordinated control of hex-IPQC converter in wind farms and corresponding implementation steps are presented in Fig. 2. Experimental and stimulation results are analyzed and clearly presented.

Hexagram Interline Power Quality Conditioner (HEX-IPQC) system model: Single line diagram of the proposed 13 bus wind energy system is shown in Fig. 1. In this, three wind generators are connected in bus numbers 1, 7 and 8 which are generator buses and remaining are considered as a load buses. Experimental data of the 225 kW WFs are utilized to identify the weak transmission lines of the buses based on the Continuation Power Flow (CPF) algorithm to place the FACTs controller as explained by Rakhmad *et al*. (2012). Hence, the proposed Hex-IPQC converter has been implemented in transmission line between bus 7 and 8. This will control the real and reactive power injection to the grid. It also maintains the voltage profile of the system under critical

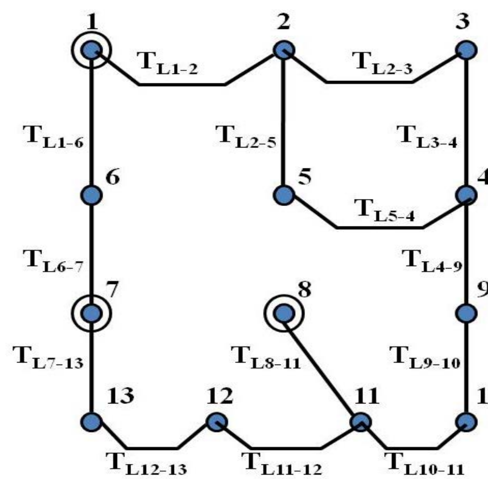

Fig. 1: Single line diagram of 13 bus wind energy system

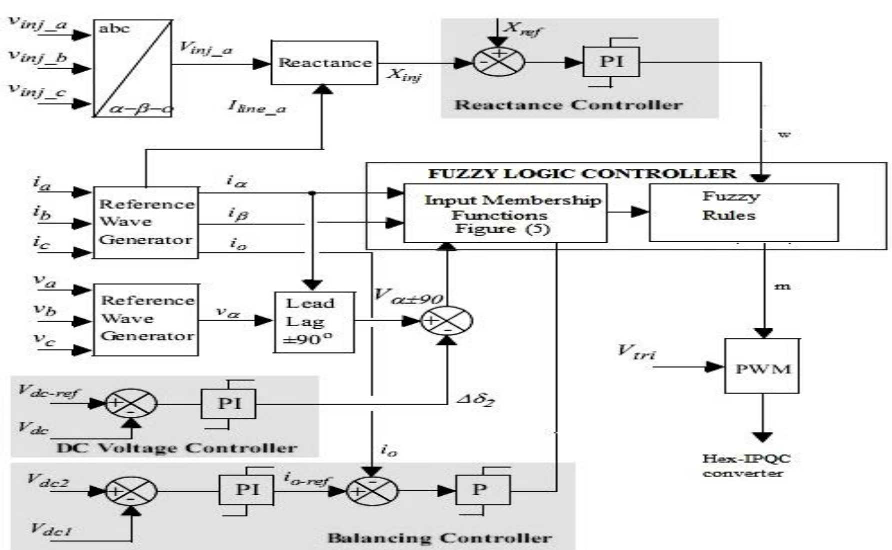

Fig. 2: Fuzzy architecture in Hex-IPQC system

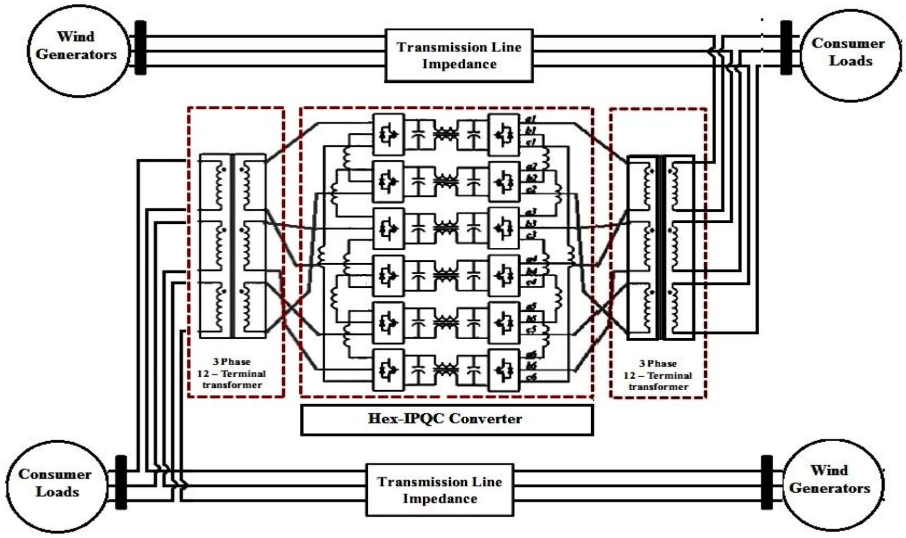

Fig. 3: Hex IPQC converter topology for grid tied tied Wfs

loading conditions. The purpose of implementing Hex-IPQC converter in between transmission line $T_{L7\text{-}13}$ and $T_{L8\text{-}13}$ is to control the real and reactive power injection to transmission lines and to record the voltage profile and its power quality. FLC system periodically monitors the co-ordinate operation of Hex-IPQC converter and wind farms parameters. Hexagram IPQC (Hex-IPQC) system made-up of twelve Voltage Source Inverters (VSI) and dc link capacitors with filter inductors as shown in Fig. 3. It also consists of two three phase transformers, with secondary windings arranged in 0°, ±30° phase shift (two are identical), to achieve harmonic current cancellation in the utility line currents leading to clean input power. The input current Total Harmonic Distortion (THD) for the VSI is about 5-6%. By proper design of zero-sequence blocking transformer the circulating current within the rectifier and inverter modules can be slow down as given:

$$\begin{cases} va1-01 = va3-03 = va5-05 = \sqrt{2vsin(\omega t)} \\ vb1-01 = vb3-03 = vb5-05 = \sqrt{2vsin(\omega t - 120^0)} \\ vc1-01 = vc3-03 = vc5-05 = \sqrt{2vsin(\omega t + 120^0)} \end{cases} \quad (1)$$

Equation 2 gives the output voltages of Mode 2, 4, 6 out of phase with Mode 2, 4, 6. The corresponding phasor diagram shown in Fig. 4b.

$$\begin{cases} va2-02 = va4-04 = va6-06 = \sqrt{2vsin(\omega t - 180^0)} \\ vb2-02 = vb4-04 = vb6-06 = \sqrt{2vsin(\omega t + 60^0)} \\ vc2-02 = vc4-04 = vc6-06 = \sqrt{2vsin(\omega t + 60^0)} \end{cases} \quad (2)$$

Output voltages of Hex-IPQC are given by Eq. 3, with the corresponding phasor diagram shown in Fig. 4c.

$$\begin{cases} VA-A = 6\sqrt{2vsin(\omega t)} \\ VB-B = 6\sqrt{2vsin(\omega t - 120^0)} \\ VC-C = 6\sqrt{2Vsin(\omega t + 120^0)} \end{cases} \quad (3)$$

The output voltages are six times that of a single VSI from Eq. 3 and the phasor diagram Fig. 4c. In other words, the voltage stress of the semiconductor switches is reduced to one sixth of a single VSI at the same output voltage and is shown in Fig. 4d.

The Hex-IPQC converters modeling equations are expressed from Eq. 1-3. The operating modes are shown in Fig. 4. It gives the Phasor diagram of Hexagram converter, to help the understanding of converter operation principle. Control the output voltages of Mode 1, 3 and 6 as given by Eq. 1 with the corresponding Phasor diagram shown in Fig. 4a.

Fuzzy controller for hexagram IPQC converter in WFs: Intelligent control method Fuzzy Logic Control (FLC) is more efficient than classical control techniques. Compare with traditional methods, FLC is faster in convergence and it improves the dynamic behavior of the system. The main purpose of FLC in Hex-IPQC system is to provide gating signal to the Hexagram converter switches, which will control the real and reactive power flow to the different transmission lines.

The Hex-IPQC gives possibility to solve the problem of controlling different transmission lines at a determined

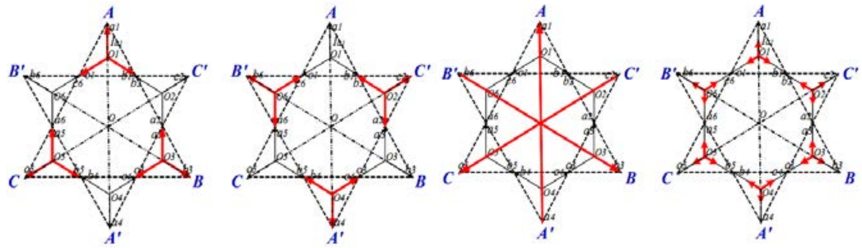

Fig. 4: Phase diagram of Hex IPQC system: a) Phase voltage of Module 1, 3, 5; b) Phase voltage of Module 2, 4, 6; (c Output voltage of hexagram inverter; d) Phase current phasor

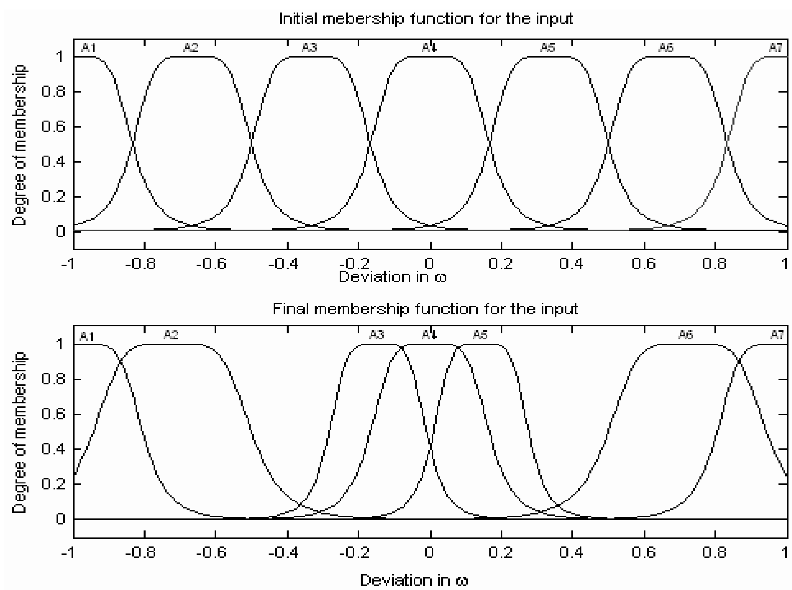

Fig. 5: Membership functions of FLC

substation. In fact, the under-utilized lines make available a surplus power which can be used by other lines for real power control. This capability makes it possible to equalize both real and reactive power flow between the lines to transfer power demand from overloaded to under-loaded lines, to compensate against line voltage drops and the corresponding reactive line power and to increase the effectiveness of a compensating system for dynamic disturbances (transient stability and power oscillation damping). Therefore, the FLC based Hex-IPQC provides a highly effective control for the power transmission at a multi-line wind energy system.

The FLC controller architecture is given in Fig. 5 and it improves overall system stability under variable loading conditions.

The distribution of initial fuzzy subset of the seven MF's (A1-A7) in the universe of discourse of input function $\Delta\omega$ is equally spaced in the range [-1, 1]. The membership functions of the resulting fuzzy inference system are calculated to perform network configuration and with the various choices of control signals under varying operating condition (Fig. 5).

RESULTS AND DISCUSSION

Hex-IPQC system design is achieved based on the experimental data of proposed 230 kW wind system. These data are collected for various operating conditions of wind system at different wind speeds as shown in Table 1. Simulation study is carried out for the proposed system and simulation results provides an knowledge to select transmission lines for locating the Hex-IPQC system. Finally the transmission lines $T_{L7\text{-}13}$ and $T_{L8\text{-}13}$ are found to be a weak line, where proposed Hex-IPQC system is implemented. Transformer selection is done through the real and reactive power generated in the above said transmission lines. To enhance system stability and improve power quality implementation of FLC control logic to the proposed system provided.

Time domain simulation of the proposed system model is given in Table 2 and Fig. 6 with the proposed

Table 1: Experimental data of the proposed 230 kW WFs

Wind Speed (m sec^{-1})	Grid real power (kW)	Grid current (A)	Grid frequency (Hz)	Net voltage (V)
2.28830	-10.27230	16.6063	49.921	677.8632
3.21900	-2.937980	21.8543	49.94	660.3921
3.78357	33.81131	37.3231	49.94	664.1362
3.94388	39.00868	40.8190	50.041	673.0026
4.10736	72.44657	66.4894	50.041	651.4521
4.23192	85.58948	77.0183	50.041	659.5449
4.38496	110.5758	97.9147	50.041	661.5898
4.62179	148.5112	128.1774	50.141	671.9574
5.33314	249.4148	212.5638	50.141	676.5598
5.42006	261.3690	223.9899	50.141	673.6297
5.98526	375.2950	322.7529	50.041	669.7300
6.32560	481.7120	414.3100	50.041	669.0710
6.34158	466.4146	400.8652	50.041	669.7141
7.08850	652.9287	554.9954	50.041	677.0266
7.39680	743.5474	647.6445	50.041	660.3109
7.85782	890.8758	773.2621	50.141	663.0012
8.25377	1106.222	957.7399	50.041	665.1268
8.20496	1220.401	1052.866	50.041	667.1144
8.96905	1427.544	1231.087	50.041	667.4374
9.18654	1636.693	1402.856	49.941	672.2927
9.26476	1659.362	1424.612	50.041	671.1183
9.73698	1795.279	1535.206	50.041	673.2474
10.20931	2034.460	1716.969	50.041	681.9464
10.34713	2050.742	1738.940	50.041	678.7811
10.72361	2296.274	1954.532	50.041	677.2366
11.32317	2468.870	2105.541	50.041	676.0736
11.26371	2454.651	2093.612	50.041	675.6907
11.53841	2508.312	2155.470	49.853	670.5206

Time domain simulation of the proposed system model is given in Table 2 and Fig. 6 with the proposed FLC controller using the MATLAB/SIMULINK toolboxes. The simulation results are presented and briefly discussed.

The dynamic behavior of the controller is verified by applying a 0.2 pu step change in the reference values of injected reactance and resistance in the Hex-IPQC system during 0.08-0.2 sec. The proposed Hex-IPQC is designed to compensate 0.4 pu of the line reactance and 0.2 pu of the line resistance in the system. The results of the above mentioned criteria are validated in simulation and results are indicated in Fig. 7-9.

This simulation results shows that voltage stability waveforms of the Wfs controlled by the FLC based Hex-IPQC system of the WFs. During critical load condition, FLC system brings WFs stability into the limit within few seconds. It is shows the effectiveness of the

Table 2: Simulation model of proposed 225 kW WFs with Hex-IPQC

CE\E	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

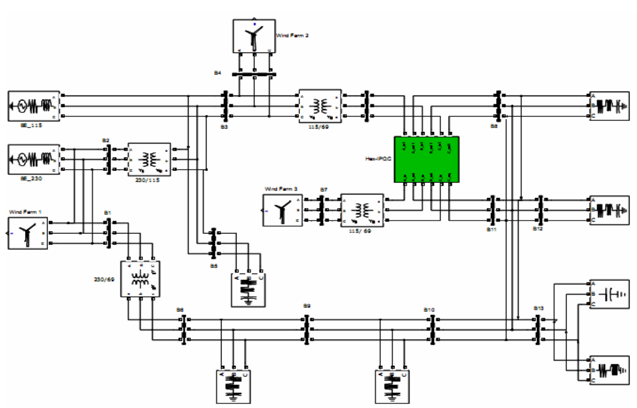

Fig. 6: Proposed fuzzy rules for Hex-IPQC system

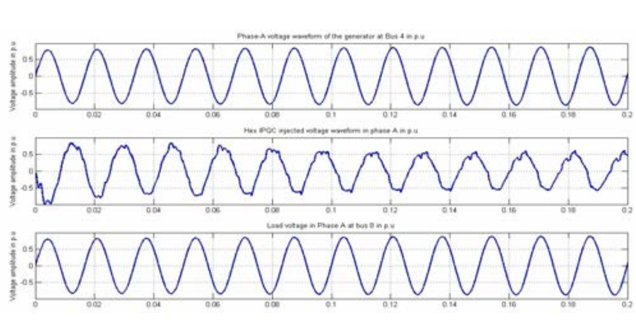

Fig. 7: Output voltage waveform of the proposed WFs under voltage sag with Hex-IPQC

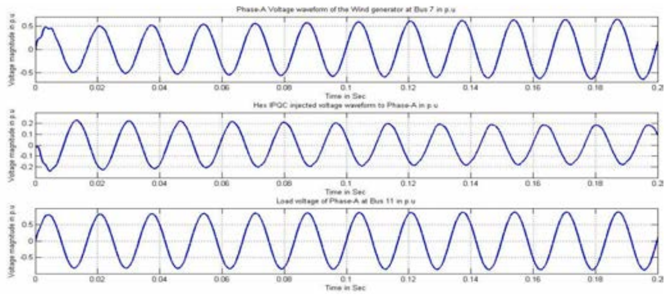

Fig. 8:Output voltage waveform of the proposed WFs under voltage swell with Hex-IPQC

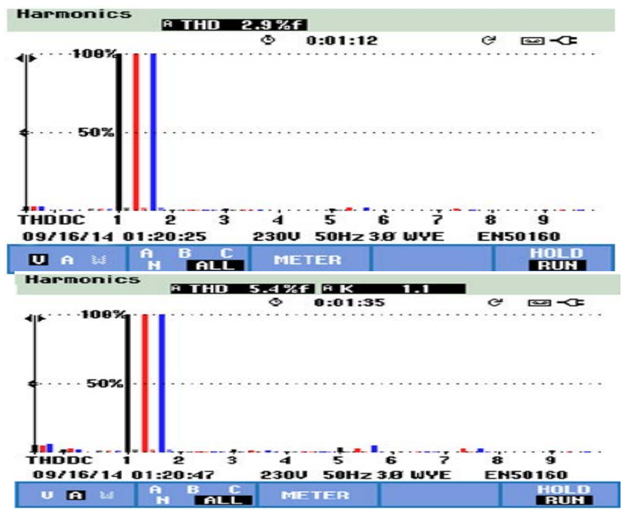

Fig . 9: Current harmonics between transmission lines T_{L7-13} and T_{L8-13}: a) Under 50% of rated load; b) the 75% of rated load

FLC system in coordinated control operation over the WFs. From the simulation and experimental results, it is observed that implementation of Hex-UPQC with FLC scheme improves the quality and shape of voltage at the load/grid as shown in Fig.7 and 8.

By adjusting the output voltage level of the Hex-IPQC's inverter. The real and reactive power injection to the grid is progressed. It was found that the THD of Hex-IPQC current signal is very low in T_{L7-13} and T_{L8-13}.

CONCLUSION

Based on experimental study for various balanced and unbalanced loads specifications of Hex-IPQC system is selected. FLC and Hex-IPQC system provides better performance control over wind farms. The system stability results are obtained within few seconds when load disturbance or power outage occurs. Simulation and experimental results of FLC are effectively verified.

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