POWER QUALITY IMPROVEMENT IN WIND ENERGY SYSTEM USING HEX-STATCOM

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Abstract: *This paper work concentrates on power quality enhancement in Wind Energy System (WES) using 3-Phase, Hexagram-Static Compensator (HEX-SC). In this surroundings, the Permanent Magnet Synchronous Generator (PMSG) based 3 kW wind energy system is employed to implement HEX-SC. The main objective of this HEX-SC is to improve the power quality in the proposed system, when WES output changes with the wind speed and also the variation of load. Furthermore, the implementation of HEX-SC reduces the power loss during low wind velocity and also due to the presence of Total Harmonic Distortions (THD) with enhanced power factor. In this research approach, the proposed system performance parameters namely frequency, output voltage and THD levels are examined for various wind velocities and variable load conditions. In addition, the excellence of HEX-SC is analyzed with Space Vector Pulse Width Modulation techniques (SVPWM). The simulation has been carried out for the proposed system using Matlab/Simulink software tool. Moreover, installing a HEX-SC in the WES will increase power transfer capability by improving the voltage stability and retaining a smooth voltage profile under different wind speed and load conditions. Finally, it has the ability to perform active filtering and also very useful for improvements in power quality.*

Key words: *Non-linear load, Static Compensator (STATCOM), Total Harmonic Distortion (THD), Wind Energy System (WES), Hexagram-Static Compensator (HEX-SC), Space Vector Pulse Width Modulation (SVPWM).*

1. Introduction

In the present circumstances, an increased prominence and anxiety for the quality of power distributed to industries, profit-making enterprises, and domestic units. This is due to an extensive usage of harmonic creating non-linear loads namely adjustable speed drives (ASD), uninterruptible power supply systems (UPS), battery charging system; switched mode power supplies (SMPS), arc furnaces and electronic fluorescent lamp ballasts etc. [1]. In addition, the distorted currents can cause the current and voltage distortions all over the system which downgrade the quality of the electric power that is supplied to customers. As time goes on, more and more equipment is being used that generates harmonics distortion in the distribution systems. Consequently, the presence of harmonics in the electrical power system leads to equipments malfunction. For example, in electric motors, the harmonic current causes AC losses in the core and copper windings. This can lead to core heating, torque pulsations, winding heating, loss of efficiency in these motors. Harmonics can also leads to result in audible noise from transformers and motors can excite mechanical resonances in electric motors and their loads. In addition, the equipment usually uses either thyristor or diode to realize power conversion on the basis of lesser component cost and a reduced amount of control complication. Conversely, the converters to produce a huge amount of harmonic currents into the electrical supply system and the consequential harmonic distortion may leads to malfunction of susceptible equipment. In order to decrease the harmonic content in the distribution system, the passive filters have been installed. Furthermore, the harmonics are amplified by the passive filters and it may degrades the power quality of the system [1], [3], [4].In order to improve the power quality in the distribution system various active filter approaches have been presented to address the harmonic issues in the power system [5-8], [15]. The active filters are employed to mitigate harmonic current and total harmonic distortion and also to restore the power factor.

However, the requirements of harmonic free current waveforms and improved power factor, under unbalanced and non-sinusoidal voltage conditions are contradictory to each other. When the supply voltage is non-sinusoidal and it is connected to an unbalanced non-linear load, any effort to get harmonic free current by establishing a shunt filter will result in a poor power factor and power quality. Correspondingly, any attempt to reduce the harmonics and improve the power factor will produce result in distorted current waveforms. Under these circumstances, an optimum performance is the best one can achieve. In this research work, proposes a new control scheme for balancing the currents and obtaining the best compromise between the power factor and current distortion under non-sinusoidal voltage conditions and it is indicated in [15]. In these situations, the application of active filters, both series and shunt type have been widely researched by various groups. An active power filter is a power electronic based custom power device (CPD) that can dynamically suppress the harmonics and compensate reactive power regardless of the changes of their amplitudes and frequencies. In this context, the application and the schemes are explained for identifying the harmonic content, which varies from one scheme to the other in [6], [7]. Generally, a Static Compensator (STATCOM) employs a pulse width modulation based switching strategy for the inverter devices in order to dynamically control the fundamental reactive component and also the harmonic components in the source current in [3]. The implementation of control algorithms with the reference current and a quick response procedure to get the control signal and simultaneously quick controlling dc-side capacitor voltage of the inverter as explained in [2], [10], [11], and [12].

In this connection various control algorithms like Space Vector Pulse Width Modulation (SVPWM) and other PWM techniques has been proposed by the researchers [2], [9], [16], [19-21]. The advantages of SVPWM over traditional controllers are that they do not need an accurate mathematical model, they can work with inaccurate inputs, can handle non-linearity, and they are more robust than conservative nonlinear controllers. In this approach, Space Vector Pulse Width Modulation (SVPWM) controller is implemented with STATCOM for the improvement of power quality under unbalanced and non-linear loads.

2. Methodologies

The power converters act as non-linear loads to AC supply system and cause harmonic insertion, lower power factor and deprived voltage regulation in AC distribution network. In addition, the single-phase load on a three-phase supply system creates an unbalance in supply current and system voltage. The unbalanced supply current and voltage affects the performance of other loads which is coupled to this system. These power quality problems were discussed and analyzed by many researchers. The implementation of HEX-SC presents improved performance than traditional methods. Several methodologies and models were used to mitigate harmonics and losses in the distribution network. The HEX-SC with SVPWM control scheme provides improved power quality during output changes with respect to the variation of wind speed and variation of load conditions. Furthermore, it decreases the power loss during low wind velocity and also THD with improved power factor as per the IEEE 519 standard.

2.1 Configuration of proposed WES

In this research work, the 3-bus wind energy test system is considered to implement and analyze the performance of proposed HEX-SC with SVPWM controller. The proposed system consists of a small wind turbine and the turbine is coupled with a Permanent Magnet Synchronous Generator (PMSG).

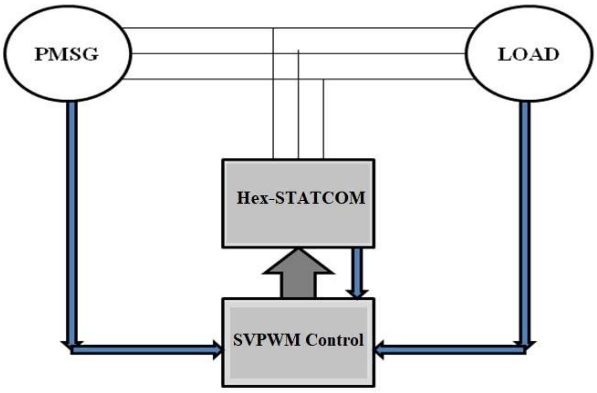


Fig. 1. Configuration of proposed WES

The configuration of proposed WES is shown in Figure 1, the bus 1 and bus 3 have connected to PMSG generator of 3 kW capacities, the PMSG generator output power changes with respect to different wind velocities and loading circumstances. The output power of oscillating generator is delivered to the load at bus 2.

2.2 Mathematical Model of the Permanent Magnet Synchronous Generator (PMSG)

A permanent magnet synchronous generator (PMSG) rated 3 kW, which is 0.75 per unit based on 4 kVA base. The rated voltage of 440 V and rated speed 600 rpm is employed in the wind energy system. The output voltage of the PMSG varies with respect to the various wind velocity and variation of load. The equation (1) indicates the mechanical output power of the wind turbine and it is given by cube law:

$$P_W = \frac{1}{2}\rho\, S\, V_W^3\, C_P\, \lambda \qquad (1)$$

Where **ρ** is the air density (kg/m^3), **S** is the surface of the turbine blades in (m^2) and $\mathbf{V_W}$ is the average wind velocity in (m/s), $\boldsymbol{C_p}$ is the coefficient of power. The equation (2) gives the tip speed ratio function.

$$\lambda = \frac{\omega_m \cdot R}{V_W} \qquad (2)$$

Where $\boldsymbol{\omega_m}$ is the mechanical speed of the rotor in (radians/sec.) and R is the radius of the blade. The equation (3) shows the output torque of the wind turbine $\boldsymbol{T_w}$.

$$T_W = \frac{P_W}{\omega_m} = \frac{\frac{1}{2}\rho\, S\, V_W^3\, C_P\, \lambda}{\lambda} \qquad (3)$$

The line to line voltage of an ideal (Loss-less and unloaded) PMSG is mentioned in the equation (4). It is expressed as follows:

$$V_L = K_v \omega_e \sin(\omega_e . t) \qquad (4)$$

Where K_V is the voltage constant and $\boldsymbol{\omega_e}$ is the electrical frequency related to the mechanical speed $\boldsymbol{\omega_m}$ by the relation. The equation (5) indicates that the electrical frequency related to the mechanical speed and is given by,

$$\omega_e = \omega_m . \left(\frac{N_P}{2}\right) \qquad (5)$$

Where, N_P is the number of poles for PMSG. The mathematical expressions from equation (1) - (5) are used to develop the Matlab/Simulink model. In the simulation model, the 3-phase PMSG is considered which provides maximum power of 3 kW at wind velocity of 12 m/s. The voltage rating is about 440V when speed of generator nearly 600 rpm. The speed of the generator varies from 160 rpm to 560 rpm at different wind velocities.

3. Configuration of Hexagram converter systems for power quality improvement

The configuration of Hexagram Converter systems is shown in the Figure 2 and it has twelve six-switch converters and their operating modes are categorized into six different modes such as Mode I, II, III, IV, V and Mode VI. The phasor diagram of hexagram converter is illustrated in the Figure 3.This phasor diagram gives the clear view about converter operation principle.

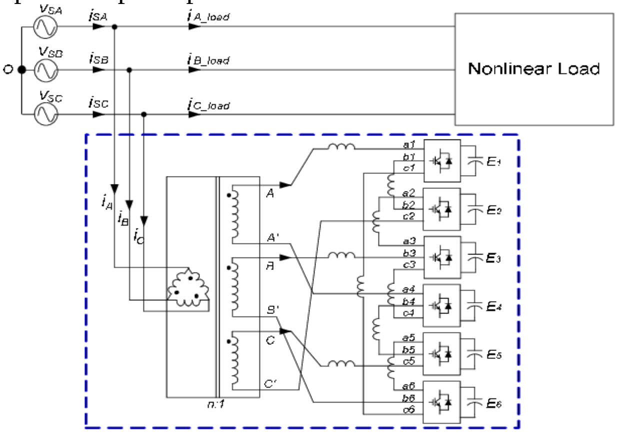


Fig. 2. Hexagram converter systems for power quality improvement

3.1 Mathematical model and analysis of the Hexagram Converter

The controlled output voltages of Mode I, III and V are given by the equation (6), with the corresponding Phasor diagram shown in Figure 3(a)

$$\begin{cases} Va1 - o1 = Va3 - o3 = Va5 - o5 = \sqrt{2}\, V\, Sin(\omega t) \\ Vb1 - o1 = Vb3 - o3 = Vb5 - o5 = \sqrt{2}\, V\, Sin(\omega t - 120^0) \\ Vc1 - o1 = Vc3 - o3 = Vc5 - o5 = \sqrt{2}\, V\, Sin(\omega t + 120^0) \end{cases} \qquad (6)$$

And also the controlled output voltages of Mode II, IV, and VI out of phase with Mode II, IV, and VI are given by the equation (7), with the corresponding Phasor diagram shown in Figure 3(b).

$$\begin{cases} Va2-o2 = Va4-o4 = Va6-o6 = \sqrt{2}\,V\,Sin(\omega t-180^{\circ}) \\ Vb2-o2 = Vb4-o4 = Vb6-o6 = \sqrt{2}\,V\,Sin(\omega t+60^{\circ}) \\ Vc2-o2 = Vc4-o4 = Vc6-o6 = \sqrt{2}\,V\,Sin(\omega t-60^{\circ}) \end{cases} \quad (7)$$

Then the output voltages of Hexagram Converter are given by equation (8), with the corresponding phasor diagram shown in Figure 3(c).

$$\begin{bmatrix} v_{a1o1} \\ v_{b1o1} \\ v_{c1o1} \end{bmatrix} = \begin{bmatrix} v_{a3o3} \\ v_{b3o3} \\ v_{c3o3} \end{bmatrix} = \begin{bmatrix} v_{a5o5} \\ v_{b5o5} \\ v_{c5o5} \end{bmatrix} = - \begin{bmatrix} v_{a2o2} \\ v_{b2o2} \\ v_{c2o2} \end{bmatrix} = - \begin{bmatrix} v_{a4o4} \\ v_{b4o4} \\ v_{c4o4} \end{bmatrix} = - \begin{bmatrix} v_{a6o6} \\ v_{b6o6} \\ v_{c6o6} \end{bmatrix} = \begin{bmatrix} \sqrt{2}Vcos(\omega t) \\ \sqrt{2}Vcos(\omega t-\frac{2\pi}{3}) \\ \sqrt{2}Vcos(\omega t+\frac{2\pi}{3}) \end{bmatrix}$$

The output voltage is expressed as the following equation,

$$\begin{bmatrix} v_{AA'} \\ v_{BB'} \\ v_{CC'} \end{bmatrix} = \begin{bmatrix} 6\sqrt{2}Vcos(\omega t) \\ 6\sqrt{2}Vcos(\omega t-\frac{2\pi}{3}) \\ 6\sqrt{2}Vcos(\omega t+\frac{2\pi}{3}) \end{bmatrix} \quad (8)$$

From equation (8) and the phasor diagram Figure 3(c), it is clearly shows that the output voltages are six times that of a single VSI. 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 it is shown in Figure 3(d).

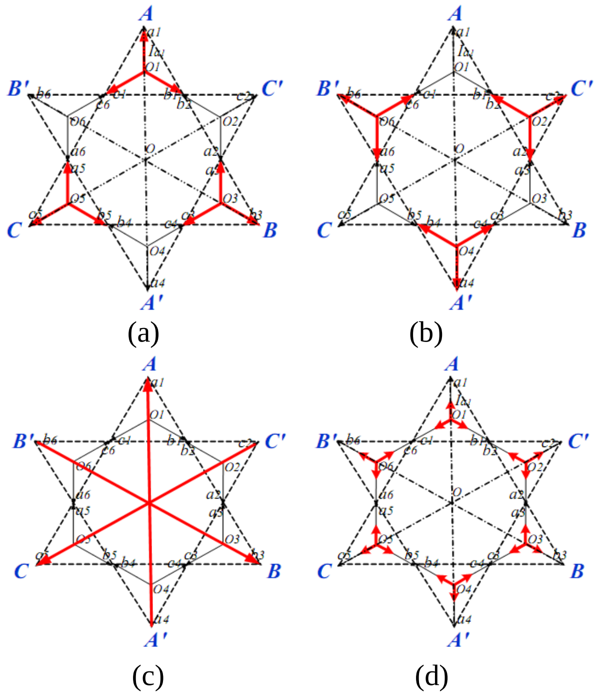


Fig. 3.Phasor diagram of Hex-SC system (a) Phase voltage of Module I, III, V (b) Phase voltage of Module II, IV, VI (c) Output voltage of Hexagram Converter (d) Phase current

The proposed HEX-SC converter has been implemented in between PMSG and variable load. It maintains the voltage profile of the system under critical load conditions. The synchronized operation of the HEX-SC converter and WES parameters are periodically monitored and controlled by SVPWM controller and this proficient controller reduces the THD content present in the WES system.

3.2 Control Schemes for HEX-SC

In this control method, PWM pulse is generated to control the HEX-SC (Inverter). The three phase load current has been considered and it is converted into αβ and dq0 using Park and Clarke transformation. This dq0- axis designates the active, reactive and reference components of the three phase currents respectively.

The differences in active component from the load current and shunt converter current has been compared and evaluated with the difference in reactive components of the both proposed SAF converter and load currents. This comparison will provide the available active and reactive currents to overcome the constraints.

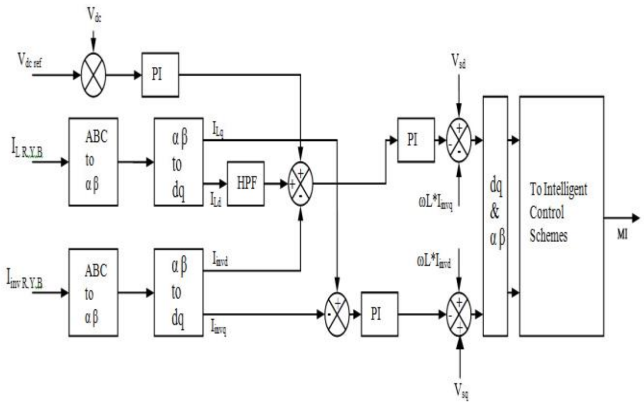


Fig. 4. PWM control structure for HEX-SC

The PWM signal is generated by converting this resultant dq0 component into three phases (abc) component using inverse Park and Clarke transformation techniques. The generated three phase reference signal with (αβ) and voltage magnitude is used to select appropriate switching segment of a HEX-SC converter using SVPWM control systems.

3.3 Space Vector PWM

SVPWM technique is the most popular one due to its effortlessness both in hardware and software, and also relatively good performance at lower modulation ratio. But the SVPWM scheme becomes very complex to achieve when the levels of the converter gets increase. Generally, a carrier based PWM with multilevel inverter can only select four switching states at most, but SVPWM can select more switching states. In general, selection of switching states has more freedom in the Space Vector PWM than the carrier based PWM. Normally, carrier based PWM mode the modulated output voltage is smooth in nature but, it contains distortion. Furthermore, the carrier based PWM technique can be useful if there are a large number of levels used in multilevel inverters. In case of matrix converter which has fixed number of switches therefore, the SVPWM technique is preferred. The carrier based PWM method with the smallest common mode voltage presents a preferable PWM technique for higher power and highest number of inverters level. The matrix converter is a non-linear controller due to the usage of non-linear components. The implementation of SVPWM technique is more suitable for the switching functions. The space vector based PWM control scheme, becomes very popular due to its simplicity and faster response. In contrast to sinusoidal PWM scheme, SVPWM treats the three phase quantities as a single equation known as space vector.

$$\left\{V_s = {}^{2}/_{3}\left\{V_a(t) + V_b(t)e^{j2\pi/3} + V_c(t)e^{j2\pi/3}\right\}\right. \quad (9)$$

Where V_a, V_b and V_c are the phase voltages. If the phase quantities are balanced three phase sinusoidal voltage, then the locus of the space vector is circular with a radius equals the amplitude of the phase voltage. The concept of space vector is derived from the revolving field of ac machine which is used for modulating the converter output voltage. In this modulation scheme the three phase quantities can be transformed to their equivalent two phase quantity either in stationary d-q frame (or) synchronously rotating frame. From this two phase component, the reference vector magnitude can be found and used for modulating the converter output. SVPWM treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency. This technique approximates the reference voltage V by a combination of the eight switching patterns (V_{ref} to V_0). The representation of rotating vector in complex plane is as shown in Figure 3.

Table 1.Switching patterns for the matrix converter and its output voltage level

a	b	c	V_a	V_b	V_c	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0	0	0	0
1	0	0	2/3	-1/3	-1/3	1	0	-1
1	1	0	1/3	1/3	-2/3	0	1	-1
0	1	0	-1/3	2/3	-1/3	-1	1	0
0	1	1	-2/3	1/3	1/3	-1	0	1
0	0	1	-1/3	-1/3	2/3	0	-1	1
1	0	1	1/3	-2/3	1/3	1	-1	0
1	1	1	0	0	0	0	0	0

The Table 1 shows the switching patterns for the matrix converter and its output voltage level. For example, if the reference voltage is positioned in sector 1, voltage vectors V1, V2, V0 and V7 would be selected and applied within a sampling period.

4. Results and Discussions

The proposed HEX-SC with SVPWM is modeled using Matlab /Simulink software tool. The Simulink model of the proposed WES with HEX-SC is shown in the Figure 5.This model shows the three phase supply system associated with the non-linear loads such as squirrel cage induction motor, Diode bridge rectifier and star connected load. Table 2 shows the modeling parameters of DC source and HEX-SC. The proposed system configuration is tested for various loads such as squirrel cage induction motor, uncontrolled diode bridge rectifier with three phase resistive load and three phase star connected loads.

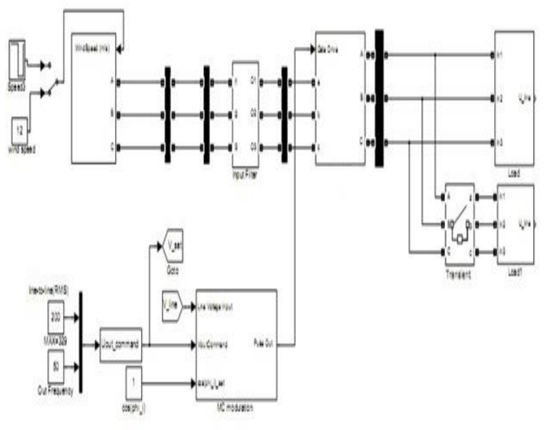


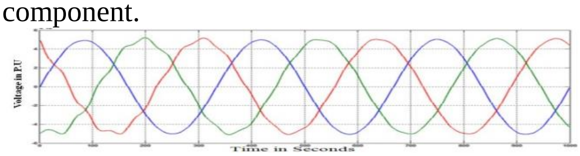
Fig.5 Simulink model of proposed WES with HEX-SC

The performance of the system is analyzed with and without presence of Hex-STATCOM. And the results are compared with and without Hex-STATCOM parameters.

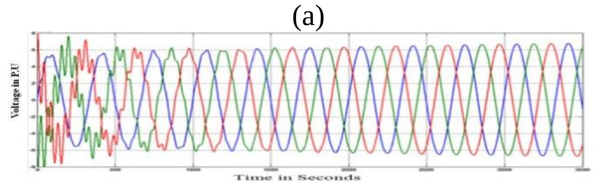
Table 2. Simulink parameters of non-linear loads

HEX-SC Parameter	
DC source (Vdc)	650 V
Parameters of Induction motor	
Machine type	Wound rotor
Power rating	4 kVA
Supply voltage	440 Volts
Frequency	50 Hz
Rated speed	1500 RPM
Stator resistance	1.405 Ω
Stator inductance	5.839 mH
Rotor resistance	1.395 Ω
Rotor inductance	5.839 mH
Mutual inductance (Lm)	0.1722 H
Parameters of 3-phase Resistive Load	
Connection type	Star connected
Resistance (R_a & R_c)	50 Ω
Resistance (R_b)	100 Ω
Uncontrolled Diode Bridge rectifier	
Resistance (R_L)	50 Ω

Due to the non-linear and unbalanced load characteristics the system will drawn different currents. This non-linear and unbalanced load conditions also injects the harmonic distortions in the system. This will leads to poor power factor and presence of high THD content. The results of the proposed system with and without Hex-STATCOM are indicated in the Figure 6. This harmonic spectrum shows the fundamental current of 25 Amps in magnitude. There is no even order harmonic present in this system. So the effect of even order harmonic is vanished. But it contains the 5 Amps of DC component.



(a)



(b)

Fig. 6. Voltage waveforms (a) With HEX-STATCOM (b) Without HEX-STATCOM

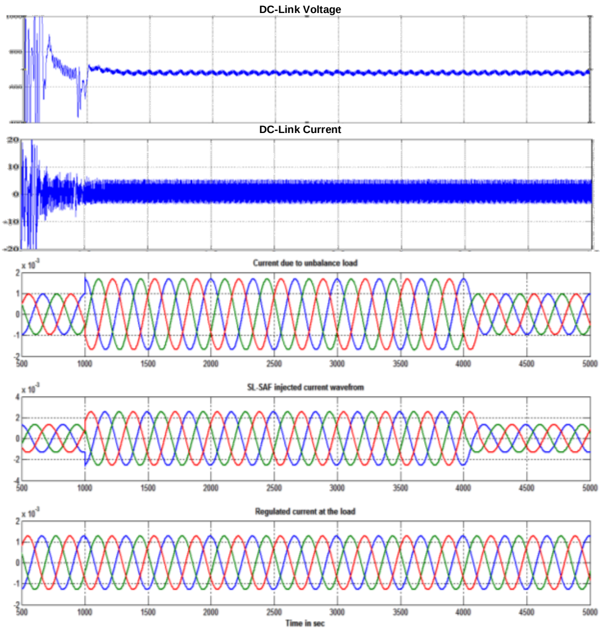


Fig. 7. DC-Link Voltage, Current and Injected current using HEX-SC under load disturbance

The injected current waveform using Hex-SC under load disturbance as illustrated in Figure 7. It is observed that the HEX-SC is connected in shunt to the distribution network. The VSIs in Hexagram converts the DC voltage across the storage device into a set of three-phase AC output voltages. These voltages are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the HEX-SC output voltages allows effective control of active and reactive power exchanges between the HEX-SC and the AC system. Such configuration allows the device to absorb or generate controllable active and reactive power. The STATCOM is connected in the power system network at 0.001 sec. The bus voltage varies within the range of 0.5 pu to 0.75 pu as shown in Figure 7. The harmonic analysis before and after HEX-SC compensation is given in Table 3.

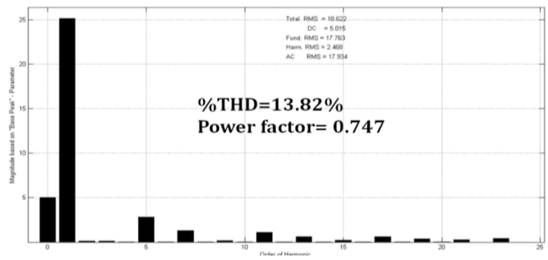


Fig. 8. Harmonic spectrums for Non-linear Load without HEX-SC

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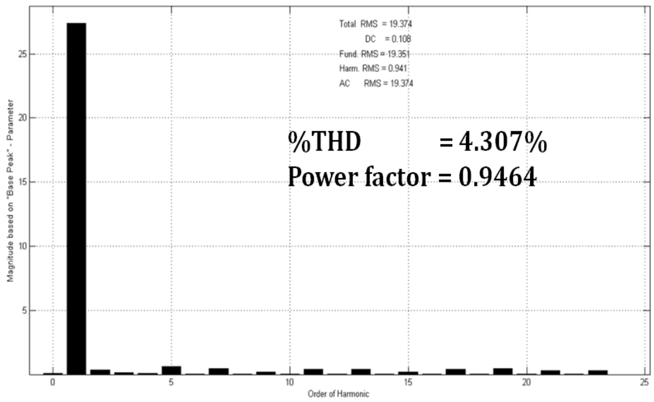

Fig. 9. Harmonic spectrums for Non-linear Load with HEX-SC

The effect of 5th order harmonic is higher than that of other odd order harmonics. The proposed system has 13.82 % of current THD content before implementation of HEX-SC compensation technique. This %THD content is compensated and eliminated into 4.307% after implementation of HEX-SC with SVPWM controller. Correspondingly, THD analysis has been carried out for various non-linear and unbalanced load conditions. The SVPWM based HEX-SC improves the power factor and power quality in the distribution system and also reduces the THD level as per IEEE 519-1992 standard by properly tuning the modulation index value of PWM signal. The results for various odd order harmonics and current magnitude are presented in Table 3.

Table 3. Harmonic Analysis before and after HEX-SC Compensation

Order of Harmonics	Before Compensation	After Compensation
	Current Magnitude in (Amps)	Current Magnitude in (Amps)
1st	28.000	25.000
3rd	0.1507	0.0316
5th	0.4520	0.6490
7th	0.3160	0.1790
9th	0.0303	0.0125
11th	0.2808	0.9356
13th	0.0048	0.5424
15th	0.3177	0.0084
17th	0.2612	0.4686
19th	0.0245	0.2836

Table 4. Comparison of THD% in HEX-SC

THD in %	
HEX-SC with conventional PWM	HEX-SC with SVPWM
13.82	4.307
12.93	4.358
10.66	4.923
11.61	5.030

The comparison of %THD level for HEX-SC with conventional PWM technique and SVPWM is presented in Table 4. The Figure 8 & 9 illustrates the harmonic spectrums for non-linear load with and without HEX-SC. From the Figure 8 & 9, It has been observed that, the power factor for the proposed WES system has been improved to the standard level (nearly 0.94) by implementation of HEX-SC. The THD content in the system under various loading conditions has been reduced by properly tuning the modulation index value of PWM signal with help of SVPWM technique.

5. Conclusion

The HEX-SC with conventional PWM controller is very simple and gives required output levels. But, it produces a considerable ripple in the output with lower order harmonics. In the proposed approach a new HEX-SC is implemented and analyzed with Space Vector Pulse Width Modulation techniques (SVPWM). HEX-SC alleviates the %THD level in the proposed WES. The SVPWM control scheme is implemented to optimize the performance of WES and generates the suitable pulses to control the hexagram converter switching functions. From the simulation results, it has been observed that the proposed method, the voltage ripple and current THD content is reduced to 4.3% under variable and unbalanced load conditions. The effectiveness of the proposed control strategy has been proved through Matlab/Simulink simulation. The proposed HEX-SC with SVPWM method provides improved power factor and good control over the power quality of the WES system.

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