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Analysis and Improved Operation of PEBB Based 5-Level Voltage Source Converter for Facts Applications

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Abstract: *The paper presents the power-electronic devices are increasing in several applications, and power-electronic building blocks (PEBBs) are a strategic concept to increase the reliability of the power-electronic converters and to minimize their cost. Magnetic elements, such as zigzag transformers, phase-shifted transformers (PST), or zero-sequence blocking transformers (ZSBT), are used to interconnect the PEBBs. In this paper, by using 5-level voltage source converter the operation of multi-pulse converters will be analyzed, describing the harmonic cancellation and minimization techniques that could be used in these multi-pulse converters, focusing on the power-electronics flexible ac transmission systems devices installed at the NYPA Marcy substation. In order to improve the dynamic response of this system, the use of selective harmonic elimination modulation is proposed and implemented.*

Index Terms: *AC–DC power conversion, power conversion harmonics, Selective harmonic elimination, pulse width modulation*

I. Introduction

The development of self-commutated switches and multilevel topologies has allowed increasing the power rate of voltage-source converters (VSCs). Due to the flexibility and controllability of the VSCs, they are used in flexible ac transmission systems (FACTS) applications, such as STATCOMs or synchronous static series compensators (SSSCs). Some objectives of these kinds of installations are to control the power flow and ensure voltage stability of the utility grids. Due to the fact that the power rate of the power-electronic devices tends to increase, high-power VSCs are needed. On the one hand, the use of multilevel converter is a suitable alternative to design high-power electronic converters. On the other hand, the power-electronic building blocks (PEBBs) can be associated, generally by using magnetic elements, in order to increase the power rate of the converters. One of the problems in FACTS applications is the output voltage harmonic quality.

The harmonic content of the voltage must satisfy the legislation requirements at the point of common coupling (PCC). Multipulse converters are used to improve the output voltage quality without increasing the switching frequency. In high-power applications, full-wave modulation is commonly used, where the switching frequency has the same value of the fundamental frequency of the output voltage.

The FACTS device installed at the New York Power Authority (NYPA) Marcy substation is presented in Section II. Three different techniques are used in this device in order to reduce the output voltage harmonic content: the harmonic cancellation, the harmonic minimization, and the use of ZSBTs. In order to control the fundamental amplitude of the output voltage, the dc bus voltage (V_{DC}) is controlled, exchanging active power.

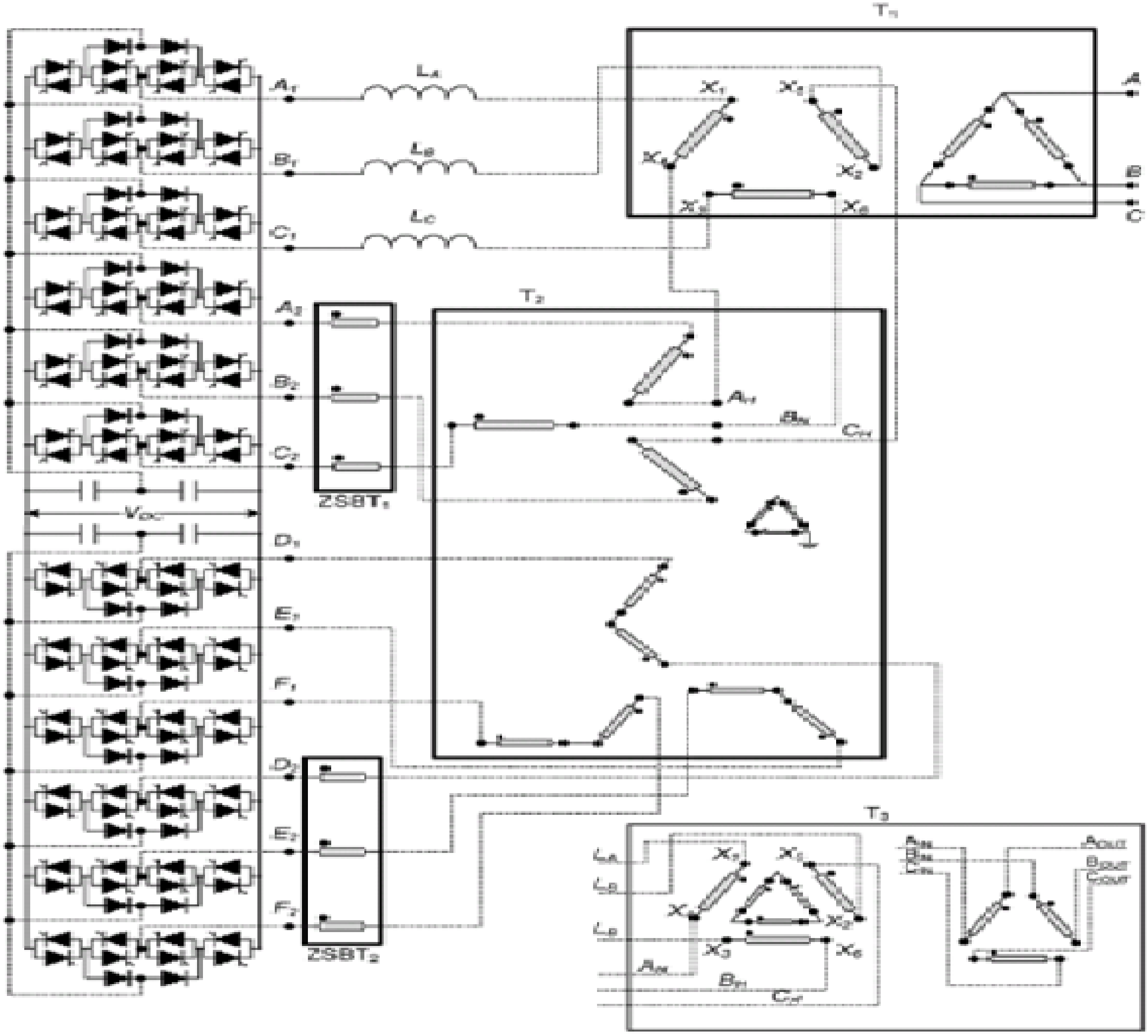

Fig No.1 Circuit diagram For Shunt and Series connected inverters

II. Proposed Five Level Voltage Source Converter

a) Harmonic Minimization by Using the Phase-Shifted Transformer:

In the previous paragraph, a method for harmonic optimization is presented where some specific harmonics are eliminated. There is another method for optimizing the harmonic content of the output voltage, where harmonics are minimized instead of eliminated, connecting in series the inverters without using the PSTs.

The same modulation is used in both inverters, so the output waveform of the inverters is exactly the same Cn . But in the first converter the waveform Cn has been shifted by$\propto$ and inthe second converter by$-\propto$ (all the angles are expressed in degrees), obtaining the voltage Vx :

$$V_x = \sum_{n=1}^{\infty} \left(C_n \cdot e^{\left(j \cdot n \cdot \frac{\alpha \pi}{180}\right)} + C_n \cdot e^{\left(-j \cdot n \cdot \frac{\alpha \pi}{180}\right)} \right)$$
$$= \sum_{n=1}^{\infty} \left(C_n \cdot 2 \cdot \cos(n \cdot \alpha) \right) \quad (2.1)$$

Where thecos$(n \propto)$ term is called the minimization rate. Thisminimization rate is the percentage of the th harmonic of theoutput voltage with respect to the original value of this th harmonic in the Cn waveform.

In Table1, the minimization rate for each harmonic, is illustrated for four different values of . The highest minimizations for a given have been highlighted.

For example, if two signals are phase shifted by +75 and -75, respectively, and then they are added, the resulting signal will have minimized harmonics 11th, 13th, 35th and 37th to the13% of the original value.

The main drawback of this harmonic minimization method is that apart from the harmonic components, the fundamental component is slightly reduced.

TABLE I
HARMONICS MINIMIZATION FOR DIFFERENT α (IN PER UNIT)

n	α=15°	α=7.5°	α=5°	α=3.75°
1	0.96	0.99	0.99	0.99
5	0.25	0.79	0.90	0.94
7	-0.25	0.60	0.81	0.89
11	-0.96	0.13	0.57	0.75
13	-0.96	-0.13	0.42	0.65
17	-0.25	-0.60	0.08	0.44
19	0.25	0.79	-0.08	0.32
23	0.96	-0.99	-0.42	0.06
25	0.96	-0.99	-0.57	-0.06
29	0.25	-0.79	-0.81	-0.32
31	-0.25	-0.60	-0.90	-0.44
35	-0.96	-0.13	-0.99	-0.65
37	-0.96	0.13	-0.99	-0.75
41	-0.25	0.60	-0.90	-0.89
43	0.25	0.79	-0.81	-0.94
47	0.96	0.99	-0.57	-0.99
49	0.96	0.99	-0.42	-0.99

b) Blocking of Zero-Sequence Voltage Components by Using Magnetic Elements:

Magnetic elements, such as zero-sequence blocking transformer (ZSBT) or [zero-sequence blocking reactor (ZSBR)], can be used to filter common-mode or zero-sequence harmonics. The impedance that ZSBT imposes to positive or negative sequences is relatively low whereas the impedance for zero sequence is relatively high.

Commonly used ZSBT with "E"-type magnetic core is shown. The three phases are wired in the central limb. The magnetic flux generated by zero-sequence currents of each phase flows through the magnetic core. However, magnetic flux generated by differential currents is cancelled out and, therefore, no flux flows through the magnetic core. The voltage drop in the ZSBT for the phase is

$$V_a = L_{LK} \cdot \frac{d\vec{i}_a}{dt} + L_{CM} \cdot \frac{d\left(\vec{i}_a + \vec{i}_b + \vec{i}_c\right)}{dt}. \quad (2.2)$$

According to for differential mode currents, them impedance imposed by the ZSBT is the leakage impedanceL_{lk}, which is relatively low. Otherwise, the inductance for zero-sequence currents is relatively high$L_{lk} + 3L_{CM}$.

c) QUASI 48-PULSE OUTPUT VOLTAGE:

The output voltage of the FACTS device shown in Fig. 1 can be a quasi 48-pulse voltage waveform. This voltage waveform is obtained by using previously described harmonic elimination and minimization techniques.

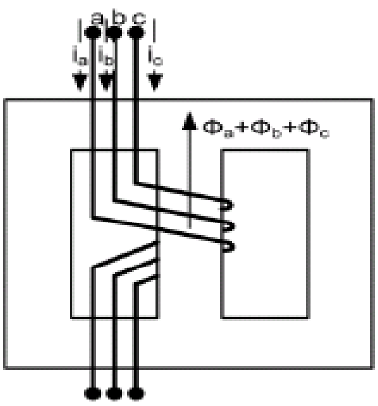

Fig 2. Zero-sequence blocking transformer with an "E" magnetic core.

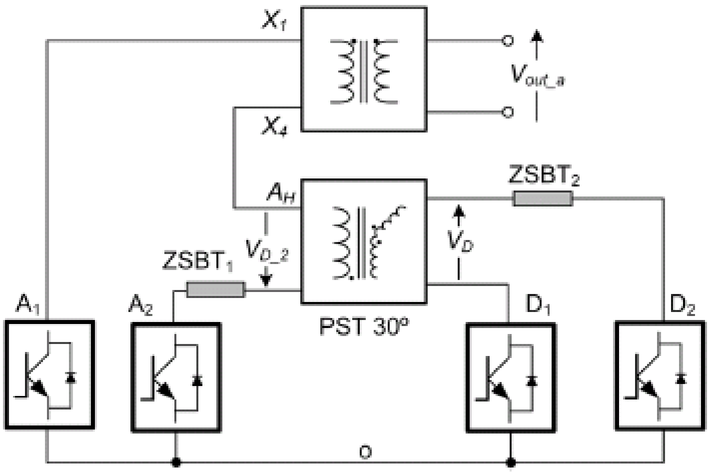

Fig.3 .Simplified single-phase circuit.

As stated previously, three techniques are used in order to eliminate harmonics: ZSBT for triplen harmonics elimination, the PST to eliminate harmonics of order$n = 6k \pm 1$ where k=1,3,5……and harmonic minimization for 11th, 13th, 23rd,25th, 35th, and 37th harmonics . In this way, the quasi 48-pulsewaveform voltage is obtained.

Voltages VA and VD-2 are added and as explained in harmonics of order $n = 6k \pm 1$where k=1, 3, 5,etc. are cancelled.

The relations between angles of the voltages shown in Fig. 7are

$$\alpha_2 = 180 - \alpha_1 \quad \alpha_3 = \alpha_1 - 30 \quad \alpha_4 = 180 + \alpha_3. \tag{2.3}$$

The angle determines which harmonic is minimized as shown in Table I. If$\propto_1$ is 7.5 , then 11th, 13th, 35th and 37^{th}harmonics are minimized. Otherwise, if$\propto_1$ is 3.75, 23rd and25th harmonics are minimized.

The voltage waveform in all of the PEBB outputs is the same (Vx) but they are phase shifted by the angles$\propto_1, \propto_2, \propto_3, \propto_4$. The voltage VD-2 is defined as given by

$$V_{D\_2} = \sum_{n=1}^{\infty} (V_{D1o} - V_{D2o}) \cdot \frac{1}{\sqrt{3}} \cdot \left(1 - e^{-j\frac{2\pi}{3} \cdot n}\right)$$
$$n = 1, 5, 7, 11, 13 \ldots . \tag{2.4}$$

This equation has taken into account the effect of the ZSBT so common-mode harmonics have not been included.

Defining the value of the angle (the angle that corresponds to the period where the voltage is zero) as , the harmonics 23rd and 25th are minimized. The angle (the phase-shift angle of the voltage with respect to the reference) is 7.5 and 11th, 13th, 35th, and 37th harmonics are minimized in the voltage across the ZSBT is

$$V_{\text{ZSBT 1}} = \frac{V'_A + V'_B + V'_C}{3}$$
$$V_{\text{ZSBT 2}} = \frac{V'_D + V'_E + V'_F}{3}. \tag{2.5}$$

And the voltage VD-2 is

$$V_{D\_2} = \frac{V_D - V_C}{\sqrt{3}}. \tag{2.6}$$

The output voltage is a quasi 48-pulse waveform and it has21 different voltage levels, 10 levels in the positive semi-period, the zero level, and 10 levels in the negative semi-period.

To summarize, in the voltage, 23rd and 25th harmonics have been minimized by imposing the angle. After that, the 11th, 13th, 35th, and 37th harmonics are minimized by setting the angle to Nevertheless, there is another option with which the same output voltage is obtained.

The 11th, 13th, 35th, and 37th harmonics of the voltage can be minimized, giving a value .The 23rd and 25th harmonics can be minimized by setting the angle. In both cases, the output voltage has the same quasi 48-pulsewaveform.

III. Use Of Advanced Modulation Strategies

The convertible static compensator implementation at the NYPA Marcy Station has been described and analyzed in the previous sections. As has been described, full-wave modulation is used by minimizing the switching power losses of the PEBBs, and harmonic elimination and minimization techniques are used in order to optimize the harmonic content of the output voltage. But the drawback of this modulation strategy is the control of the amplitude of the fundamental output voltage. There are two ways to control the amplitude of the output voltage:

1) Changing the angle; but the change of this angle means that the harmonics are not going to be minimized;

2) Changing the dc bus voltage; the dynamic response of the converter is very slow and the system becomes nonlinear using this alternative..

In the SHE modulation, the switches of the power converters are switched several times per period producing notches in the output voltage of each PEBB, Controlling the angle at which the switches are commutated, the amplitude of several harmonics can be controlled. These degrees of freedom are used to control the amplitude of the fundamental component, and to cancel different harmonics. The following equation defines the amplitude of the output voltage harmonic for a three-level converter:

The studied application is based on three-level NPC PEBBs. Therefore SHE modulation is focused on three-level signals. The first quadrant is defined by the three angles whereas the second quadrant and the third and fourth quadrants are obtained by applying quarter-wave and negative half-wave symmetries, respectively.

One of the disadvantages of SHE is that nonlinear equations must be solved. Moreover, the complexity tends to increase when more angles are introduced and when higher order harmonic equations must be solved.

Instead of eliminating specific harmonics, they can be reduced by using selective harmonic mitigation (SHM) modulation. This method has the advantage that more than one harmonic can be reduced for each commutation angle .Three possible modulation alternatives are analyzed in the following paragraphs, using selective harmonic elimination or mitigation techniques with three angles.

A. Elimination of 11th and 13th Harmonics by Applying SHE Modulation (SHE I):

SHE modulation with three angles is applied to each PEBB in order to control the fundamental component and to eliminate the 11th and 13th harmonics. Consequently, the switching frequency is three times higher compared to full-waveform modulation, but in this case, the fundamental amplitude is controlled by the modulation and not by the level of the dc bus voltage.

Another degree of freedom is available that is the angle shown given , the value of 3.75 , 23rd and 25thharmonics is minimized up to 6.5%.

As stated previously, all the harmonics of order$n = 6k \pm 1$where k=1, 3, 5, etc are eliminated by the phase shifted transformerT2 of Fig. 1. Therefore, the first significant harmonics of are harmonics of order 35 and 37.

B. Elimination of 23rd and 25th Harmonics by Applying SHE Modulation (SHE II):

As in the previous section, SHE modulation with three angles is applied to each PEBB output voltage. In this case, the first angle is used to control the fundamental amplitude and the other two angles are used to eliminate harmonics of order 23 and 25.

The angle is 7.5 with which harmonics of order 11, 13,35, and 37 are minimized up to 13%. All harmonics of order $n = 6k \pm 1$, where k=1, 3, 5, etc. are eliminated by the phase-harmonics shifted transformer T2 of Fig. 1. Thus, the first relevant harmonics of output voltage are harmonics of order 47 and 49.

C. Elimination of 11th and 13th and Minimization of the 23rdand 25th Harmonics by Applying SHE Modulation (SHE III):

In this third alternative, the amplitude of the fundamental component is not controlled by the SHE modulation angles. Instead, the SHE modulation works with fixed pre calculated angles that eliminate the 11th and 13th harmonics. Different families of angles that eliminate these two harmonics are calculated, and the optimal operation point is selected among all of these families, choosing the angles that, with a high modulation index, generate very small amplitude 23rd and 25th harmonics.

The “optimum” angles selected in our case generate a fundamental amplitude of 0.88 p.u., eliminate the 11th and 13th harmonics, and minimize the amplitude of the 23rd and 25th harmonics. Thus, the SHE modulation works at a fixed point. The selected three angles of the SHE modulation are shown

$$\beta_1 = 21.08^\circ \quad \beta_2 = 54.08^\circ \quad \beta_3 = 57.46^\circ. \tag{2.6}$$

The amplitude of the fundamental component is controlled by shifting the angle $\propto_1$. As stated previously, all harmonics of order$n = 6k \pm 1$ where k=1, 3, 5, etc are eliminated by the phase-shifted transformerT2.

IV. Simulation Results

In this section, simulation results with the proposed modulation strategies have been carried out in Mat lab7.8 version and in the Simulink. The optimum working point of each modulation, taking into account the THD and the modulation index, has been chosen as a working point for the simulation. The angles of the SHE modulations and the modulation index are mentioned.

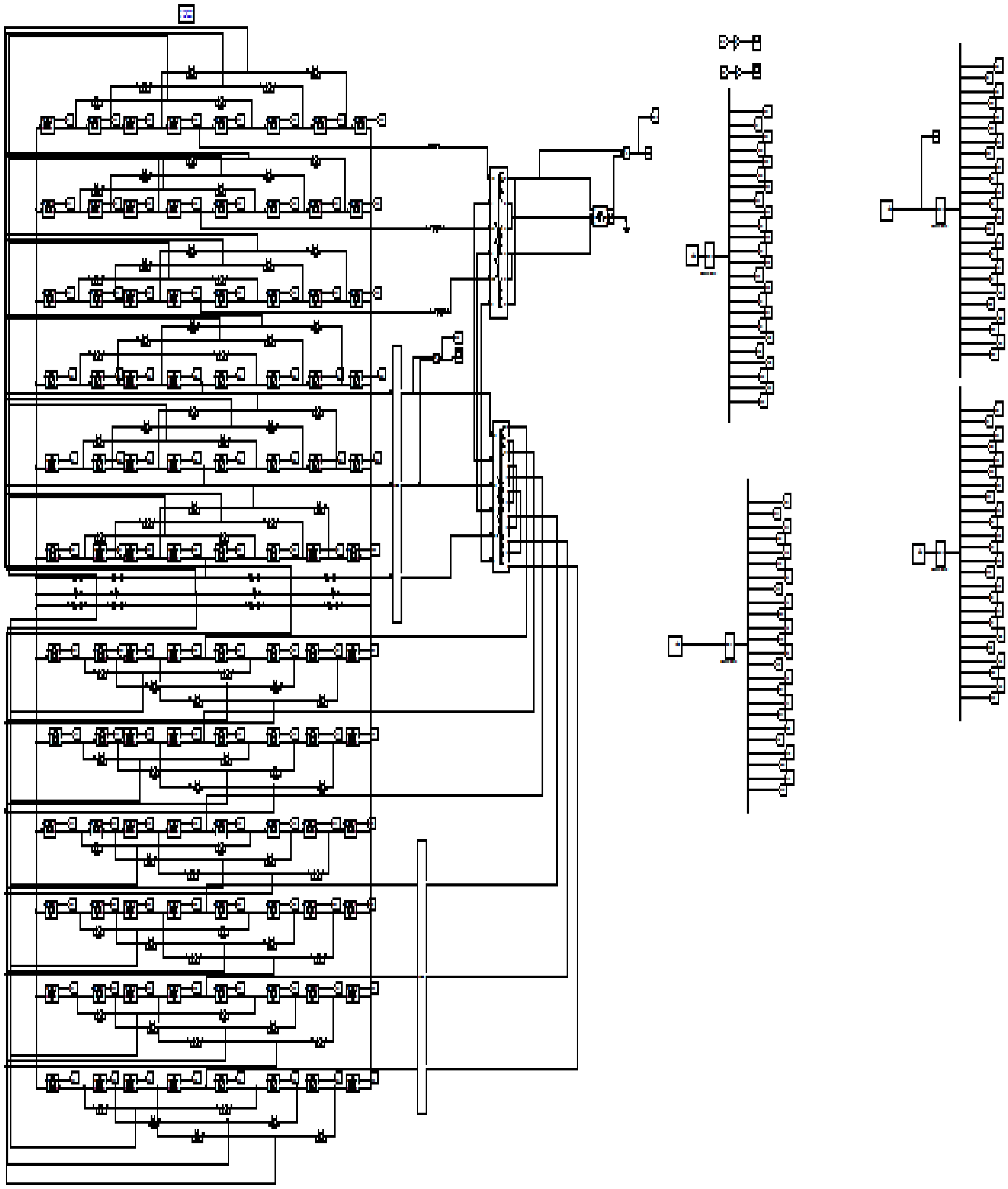

Fig 5. Simulation Circuit Diagram for Five-level Voltage Source Converter Based PEBB

V. Output Waveforms Of Propsed System

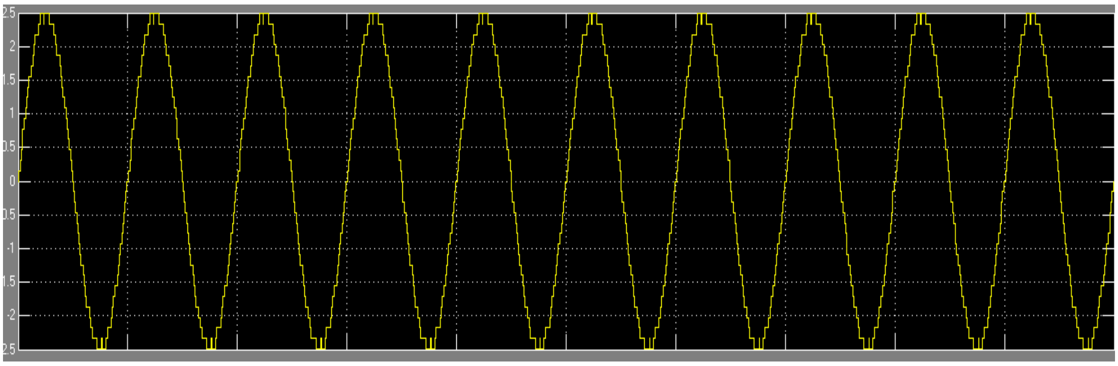

Fig 6. Vout Voltage normalized with respect to voltage Vdc for given modulation.

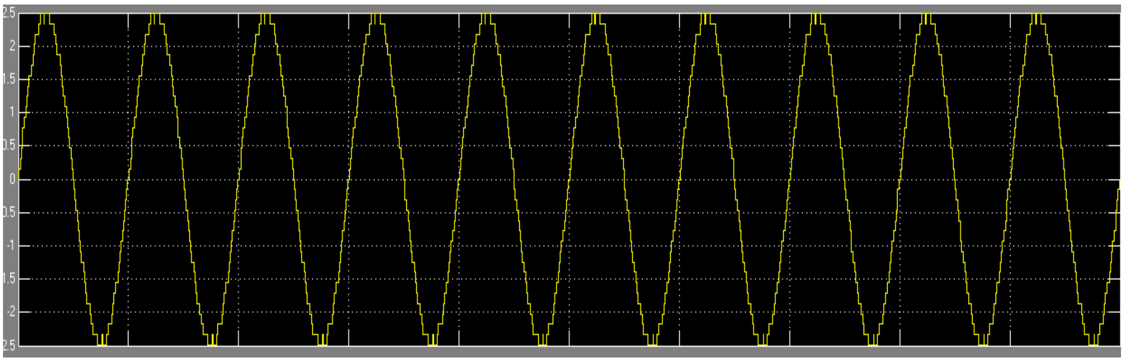

Fig 7.Vzsbt Voltage normalized with respect to voltage Vdc for given modulation

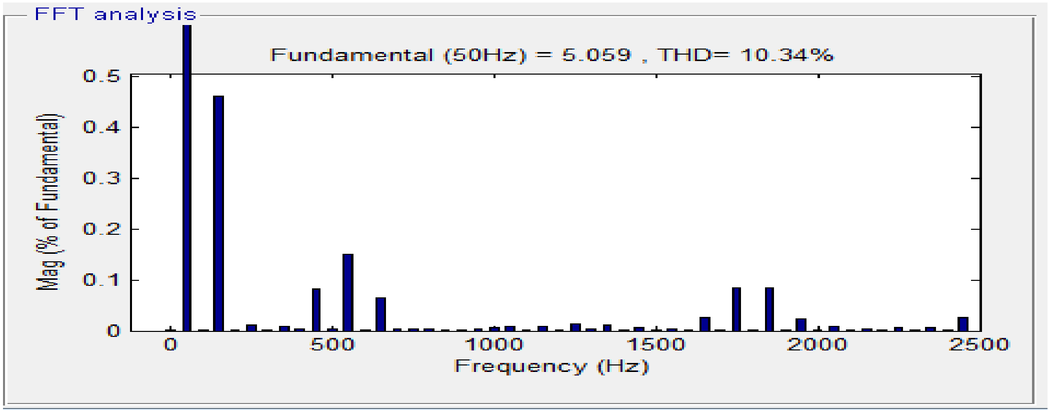

Fig 8. Vout Total harmonic content with respect to Vdc for given modulation

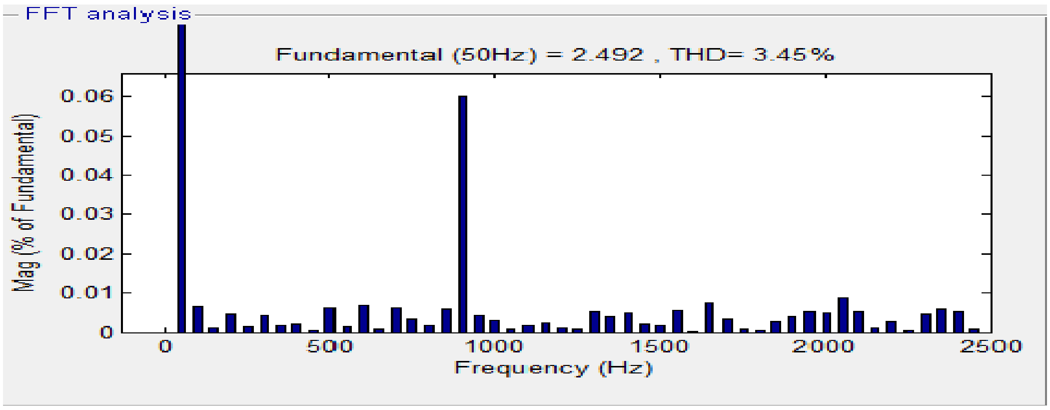

Fig 9. Vzsbt Total harmonic content with respect to Vdc for given modulation

VI. Conclusion

In this paper a by using five level voltage source converter is used to new the harmonic cancellation and minimization in multipulse converters has been analyzed and described, focusing on VSC power-electronics converters using PEBBs for FACTS applications. The convertible static compensator implementation at the NYPA Marcy Station has been described and analyzed for this purpose. The harmonic elimination and minimization techniques used in this multipulse VSC have been explained. In this system the total harmonic content and can be used and increase the performance of the system.

The study can be used as a base to understand the association of PEBBs by using magnetic elements and increase the dynamic response of the system and improve facts applications.

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