# Hybrid Power Quality Compensator Interfaced With Fuzzy for High-Speed Locomotive Systems

Daniel Manoj Nethala
Assistant Professor
Department of EEE, St.Martin's Engineering College, Dhulapally, Secunderabad, TS

**Abstract- Implementation of fuzzy logic controller in place of classical controller attains good response, low THD values, voltage as feedback for significantly improving the dynamic performance of proposed HPQC module. With increase in traffic and speed railway became one of the major load on supply grid. AC-DC converters used in locomotive of traction system draws rich harmonics content current results in poor power quality and failure or missed operation of utility causing derating of grid and affect the reliability. A hybrid power quality compensator (HPQC) is proposed for comprehensive compensation under minimum dc operation voltage in high-speed traction power supplies. Reduction in HPQC operation voltage can lead to a decrease in the compensation device capacity, power consumptions, and installation cost. It is shown through simulation results that similar compensation performances can be provided by the proposed HPQC with reduced dc-link voltage level compared to the conventional railway power compensator. The co phase traction power supply with proposed HPQC is suitable for high-speed traction applications. In this study, the renewable energy sources are used as the supply to the proposed concept. For the high response and achieving the fast steady the system can be controlled the proposed concept with the fuzzy logic controller.**

*Index Terms*—**Co Phase System, Power Quality Compensator, Fuzzy Controller, Reactive Power Compensation, Traction Power, Unbalance Compensation.**

## I.INTRODUCTION

With the rapid development of power electronics, Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be utilized to control power flow and enhance system stability. The electric railway is in a competition with other possibilities of transportation. The locomotives became faster and faster and in consequence their power is growing as well. The high power locomotives pollute the supply system with harmonics. In order to ensure the voltage quality of the whole energy system, it is necessary to reduce this pollution [1]. Strict requirements were established on the voltage quality of the electric supply network in the last decade. One of these requirements is in connection with the harmonic distortion of the voltage [2]. The voltage distortion is caused by the non-linear loads connected to the network on different voltage levels. The non-linear loads act as virtual harmonic current generators. Utility companies can refuse consumers to be connected to the network injecting high current harmonics.

To reduce the negative sequence, the high-speed and overload electrified railway traction transformer uses the V connection transformer. Two single-phase power of the secondary side of the transformer turns in provide energy to locomotives load, commonly known as split-phase power supply [3]. V connection transformer has simple structure, low manufacturing costs, but can reduce half of the negative sequence current caused by the load at most. In the future, along with the increase of high-power electric locomotive power and increase of transport capacity lines, negative sequence caused by high-speed and heavy-duty electric railway will deteriorate further. Then one three- phase to single-phase symmetrical power supply system (also known as co phase power supply system) which applying to electric railway eliminates the negative sequence is of great significance to enhance the development of high-speed and heavy load of electrified railway carrier.

The cost is low of the former, but the poor dynamic performance; the latter is real-time, but the cost is high. Combine the features of both, the literature, passive and active hybrid integrated compensation was proposed. At the same time, compensation characteristics and capacity configuration are discussed, but they did not cancel the secondary side of the transformer commutation link. In this paper, a hybrid device combining active and passive compensators, named as the hybrid power quality compensator (HPQC), is proposed for compensation in co phase traction power supply [4]-[6]. The parameter design procedure for minimum HPQC voltage operation as well as the minimum voltage rating achievable is discussed.

## II.CONVENTIONAL AND PROPOSED SYSTEM CIRCUIT CONFIGURATIONS

In this paper, the substation transformer is composed of two single-phase transformers, and is commonly known as the V/V transformer. The three-phase power grid is transformed into two single-phase outputs (Vac and Vbc phases) through V/V transformer. The locomotive loadings are all connected across the same single phase output (Vac), leaving another phase (Vbc) unloaded. The RPC is composed of one back-to-back converter and is connected across the Vac and Vbc phases, so as to provide power quality compensation for the system. The circuit configuration of the proposed co phase traction power supply with HPQC is shown in Fig. 1. In contrast to conventional structure, the converter is connected to the Vac phase of the transformer via a capacitive coupled hybrid LC structure. As will be discussed later, this results in the reduction of converter dc bus voltage of HPQC. The compensation algorithm of the proposed HPQC is similar to that in conventional RPC and is not discussed here. Details may be found in [7]. For better understanding of the discussions, the detailed structure and physical definitions of RPC in the conventional structure and HPQC in the proposed structure are presented in Fig. 2.

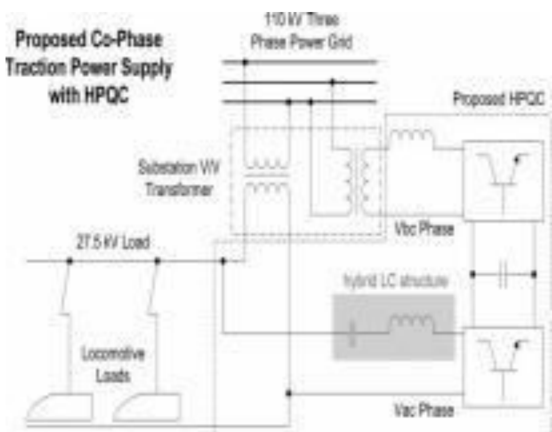
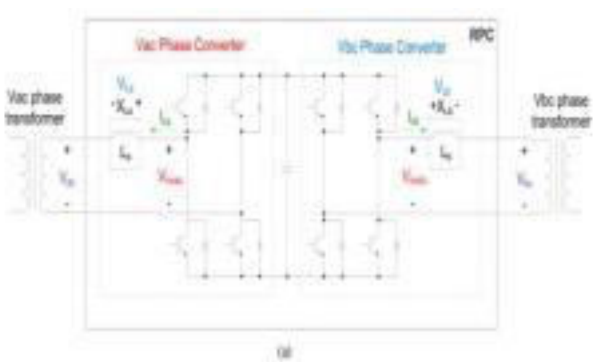



Fig.1. Circuit configuration of the proposed co phase traction power supply with HPQC.



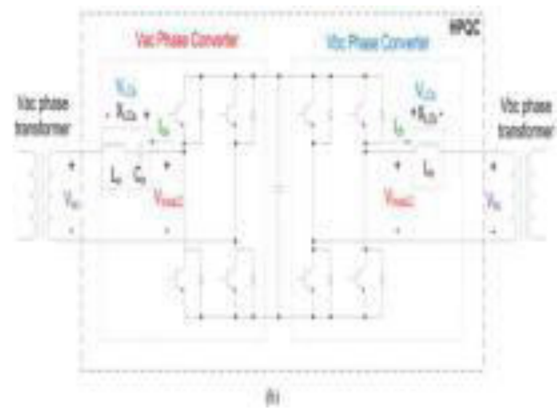




Fig.2. Detailed structure and physical definitions of (a) RPC in the conventional co phase traction power and (b) HPQC in the proposed co phase traction power.

Since traction loads are mostly inductive, the following contents are discussed based on the assumption of inductive loadings. The vector diagrams of the Vac phase converter for the conventional RPC and proposed HPQC are shown in Fig. 3. It can be observed that with capacitive coupled LC structure, the amplitude of Vinva LC in HPQC can be less than that of Vinva L in RPC under the same compensation current. The corresponding mathematical expressions are shown in (1) and (2). With capacitive coupled structure in HPQC, XLCa is of negative value, and it results in reduction of Vinva LC. Details of compensation current in co phase traction power may be found [8].

$$|V_{\mathrm{inva}L}| = \sqrt{V_{\mathrm{inva}Lp}^2 + V_{\mathrm{inva}Lq}^2} = \sqrt{(V_{ac} + |I_{caq}|\, X_{La})^2 + (|I_{cap}|\, X_{La})^2} \quad (1)$$

$$|V_{\mathrm{inva}LC}| = \sqrt{V_{\mathrm{inva}LCp}^2 + V_{\mathrm{inva}LCq}^2} = \sqrt{(V_{ac} + |I_{caq}|\, X_{LCa})^2 + (|I_{cap}|\, X_{LCa})^2} \quad (2)$$

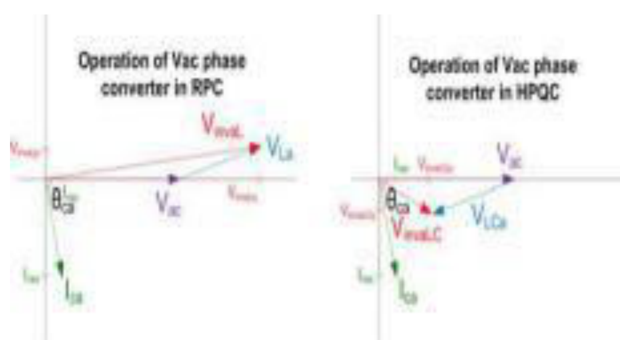



Fig.3 Vector diagram showing the operation of Vac phase converter in (a) RPC of the conventional structure and (b) HPQC of the proposed structure.

Vac coupled impedance in RPC and HPQC under load PF of 0.85 .The figure shows clearly that under the examined

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condition, the value of Vinva L in RPC is higher than that of Vinva LC in HPQC. Moreover, there is a minimum voltage operation point for HPQC. For instance, with load PF of 0.85, the minimum value of Vinva LC in HPQC is approximately 48% of Vac phase voltage. The operation point can be tuned along the curve by changing the Vac coupled impedance. Therefore, the HPQC operation could be located at the minimum voltage operation point via specific parameter design. The detailed discussions are given in the next section [9].

## III.HPQC PARAMETER DESIGN FOR THE MINIMUM DC VOLTAGE OPERATION

The parameter design for the minimum dc voltage operation of HPQC in the proposed structure is being explored in this section. The design procedures of Vac and Vbc phase coupled impedance are introduced, together with the investigations on the minimum HPQC dc voltage rating achievable.

### *A. Vac Phase Coupled Impedance Design*

The vector diagram showing the operation of Vac phase converter in HPQC under minimum voltage operation. With constant load PF and capacity, the vector Ica is fixed. Thus, the vector VLca would vary along the line L1 as the Vac coupled impedance XLCa varies. It can be observed that the amplitude of Vinva LC can be minimized when it is perpendicular to the vector VLCa. In other words, the minimum amplitude of Vinva LC occurs when the compensation current Ica is in phase with the voltage Vinva LC. By further defining the power angle of Ica as θca, the mathematical relationship in (3)

$$V_{LCa}\left[V_{\mathrm{inva}LC\_\mathrm{min}}\right] = I_{ca}X_{LCa} = V_{ac}\left(\sin\theta_{ca}\right) \tag{3}$$

The corresponding Vac coupled impedance XLCa required for minimum Vinva LC can, thus, be determined as shown in

$$X_{LCa}\left[V_{\mathrm{inva}LC\_\mathrm{min}}\right] = \frac{V_{ac}\left(\sin\theta_{ca}\right)}{I_{ca}}$$

(4) With the aforementioned analysis, only the Vac coupled impedance design for minimum HPQC voltage operation is determined. However, the ultimate goal of a parameter design is to determine the Vac phase coupled inductance La and capacitance Ca for practical application. The linkage of XLCa with Ca and La can be obtained through circuit analysis, as shown in

$$X_{LCa}\left[V_{\mathrm{inva}LC\_\mathrm{min}}\right] = \frac{V_{ac}\left(\sin\theta_{ca}\right)}{I_{ca}} = -\left(\frac{\omega^2 L_a C_a - 1}{\omega C_a}\right) \tag{5}$$

For example, with Vac of 27.5 kV, load PF of 0.85, and capacity of 15 MVA, the variation of La and Ca which satisfies the relationship in (5) is presented. It can be observed that the relationship between La and Ca for minimum HPQC voltage rating is nonlinear. It is more practical for smaller physical size of lower inductance value. Furthermore, there is a limitation on the value of Ca, which is indicated by the large dot. This is also the Ca value boundary. For a Ca value exceeding this boundary, the HPQC drops into the inductive coupled region, causing the operation similar to RPC. Minimum voltage operation in HPQC, thus, fails when the value of Ca is outside this boundary.

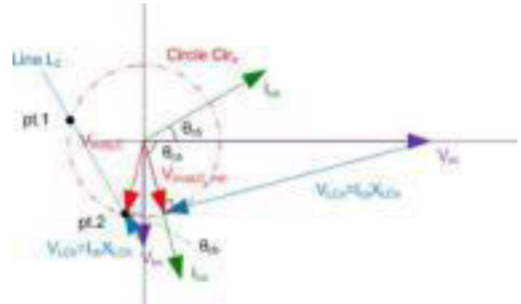


Fig. 4.Vector diagram showing the operation of HPQC in correspondence with minimized Vinva LC.

### *B. Vbc Phase Coupled Impedance Design*

For the Vbc phase coupled impedance design, it is determined with matching to the minimum voltage Vinva LC min. The vector diagram showing the operation of Vbc phase converter in HPQC in correspondence with the Vinva LC min is shown in Fig. 4. The minimum HPQC voltage is represented by the circle Cira with radius Vinva LC min. assuming constant load PF and capacity, the vector VLC b varies along the line L2 with varying Vbc phase coupled impedance XLCb. Two intersection points (pt.1 and pt.2) are present between the circle Cira and the line L2. These two points are the operation points which satisfy the voltage matching with Vinva LC min. They may be determined mathematically. The mathematical expression showing the intersection of circle Cira and the line L2 is given in

$$V_{\mathrm{inva}LC\_\mathrm{min}}^2 = \left(V_{LCb}^2 \sin^2\theta_{cb} + \left(V_{bc} - V_{LCb}\cos\theta_{cb}\right)^2\right) \tag{6}$$

By solving the expression, the mathematical expressions for pt.1 and pt.2 can be obtained in

$$(\mathrm{pt.2})\frac{V_{bc}\cos\theta_{cb} - \sqrt{V_{\mathrm{inva}LC\_\mathrm{min}}^2 - V_{bc}^2\sin^2\theta_{cb}}}{I_{cb}} = X_{LCb} = \frac{V_{bc}\cos\theta_{cb} + \sqrt{V_{\mathrm{inva}LC\_\mathrm{min}}^2 - V_{bc}^2\sin^2\theta_{cb}}}{I_{cb}}(\mathrm{pt.1}) \tag{7}$$

Although both pt.1 and pt.2 may satisfy the voltage matching with Vinva LC min, operation point at pt.2 is preferred due to the lower impedance of XLCb and lower power consumptions. Besides the Vbc coupled impedance of XLCb, there is another issue concerning about the value of Vbc. For the circle Cira to have intersections with the line L2, the expression for XLCb in (7) must be real values. Thus, the restrictions in (8) can thus be obtained

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$$V_{bc} \leq \frac{V_{\text{inva}LC\_\text{min}}}{\sin\theta_{cb}} \quad (8)$$

### *C. Minimum HPQC Voltage Rating Achievable*

After investigations of the *Vac* and *Vbc* phase coupled impedance design for the minimum HPQC operation voltage, the minimum voltage rating achievable is discussed in this section.

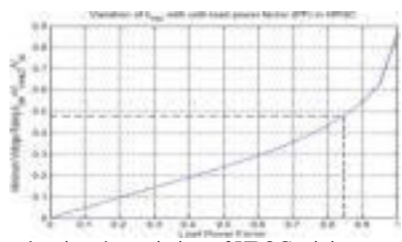


Fig. 5.Curve showing the variation of HPQC minimum voltage rating (k_min) with load PF.

The value of $V_{inva}$ LC min is a key factor in the minimum HPQC voltage rating achievable. By substituting the design of Vac coupled impedance XLC an in (4) into the HPQC Vinva LC voltage calculation in (2), the minimum value of $V_{inva}$ LC in HPQC ($V_{inva}$ LC min) can be obtained in

$$V_{\text{inva}LC\_\text{min}} = (\cos\theta_{ca})V_{ac} \quad (9)$$

Neglecting the effect of Vac phase voltage, the minimum HPQC voltage rating is determined by

$$k_{\text{min}} = \frac{V_{\text{inva}LC\_\text{min}}}{V_{ac}} = \cos\theta_{ca} \quad (10)$$

It is now obvious that the minimum HPQC voltage rating is dependent only on the power angle of Ica. This again correlates with the load PF, as expressed in

$$\theta_{ca} = \tan^{-1}\left(\frac{\frac{1}{2\sqrt{3}}\text{PF} + \sin(\cos^{-1}(\text{PF}))}{\frac{1}{2}\text{PF}}\right) \quad (11)$$

The curve showing the variation of minimum HPQC voltage rating ($k_{min}$) against load PF is plotted. It is equivalent to joining all the minimum operation points of the mesh plot. Under different load PF. For example, with load PF of 0.85, the minimum voltage rating is approximately 0.48, which is consistent with the analysis in Section II. Assuming Vac phase voltage of 27.5 kV, the minimum value of $V_{inva}$ LC achievable is, thus, 13.2 kV. The peak Value of the Vac phase voltage is 38.89 kV, and the minimum HPQC dc-link voltage required is √2 times of $V_{inva}$ LC, which is approximately 18.67 kV.

## IV.CONTROL PHILOSOPHY

The control block of the system is shown in Fig. 6. The instantaneous load active and reactive power is computed using the modified instantaneous pq theory.

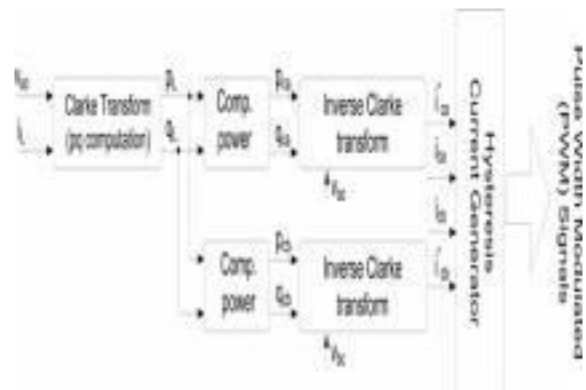



Fig. 6.Control block diagram of the HPQC for co phase traction power supply compensation.

The mathematical expression is shown in (12), in which $V_{ac}$ and $i_L$ are the load voltage and current rms, while $V_{acd}$ and $i_{Ld}$ are 90◦ delay of load voltage and current, respectively. $p_L$ and $q_L$ refer to the instantaneous load active (real) and reactive (imaginary) power.

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} v_{ac} \cdot i_L + v_{acd} \cdot i_{Ld} \\ v_{acd} \cdot i_L - v_{ac} \cdot i_{Ld} \end{bmatrix}$$

The active power part $p_L$ can be split into dc part $p_{dc}$ which corresponds to the fundamental average active load power; and oscillating part $p_{ac}$ which corresponds to the oscillating active power between system source and load and contributes as part of harmonics and reactive power (which need to be compensated). The mathematical expression is shown in

$$p_L = p_{dc} + p_{ac}$$

The required compensation power is then computed according to the power quality requirement, as expressed in (14), where $p_{ca}$ and $q_{ca}$ are the required active and reactive compensation power from the Vac phase converter, while $p_{cb}$ and $q_{cb}$ are the required active and reactive compensation power from the Vbc phase converter

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} \frac{1}{2}p_{dc} + p_{ac} \\ \frac{1}{2\sqrt{3}}p_{dc} + q \\ -\frac{1}{2}p_{dc} \\ -\frac{1}{2\sqrt{3}}p_{dc} \end{bmatrix}.$$

The reference of $V_{ac}$ and $V_{bc}$ phase compensation current, $i^*_{ca}$ and $i^*_{cb}$, can then be computed according to (15) and (16), where $V_{bc}$ and $V_{bcd}$ are the $V_{bc}$ phase voltage and its 90◦ delay value

$$i_{ca}^{*} = \frac{1}{v_{ac}^{2} + v_{acd}^{2}} \begin{bmatrix} v_{ac} & v_{acd} \end{bmatrix} \begin{bmatrix} p_{ca} \\ q_{ca} \end{bmatrix}$$

$$i_{cb}^{*} = \frac{1}{v_{bc}^{2} + v_{bcd}^{2}} \begin{bmatrix} v_{bc} & v_{bcd} \end{bmatrix} \begin{bmatrix} p_{cb} \\ q_{cb} \end{bmatrix}$$

The computed reference current signal is then sent to the hysteresis current controller, which pulse width modulated signals are generated for the electronic switches of $V_{ac}$ and $V_{bc}$ phase converters. The HPQC balances the grid-side current by transferring active power from the $V_{ac}$ phase to the $V_{bc}$ phase. Meanwhile, harmonic and reactive power compensations are achieved by the $V_{ac}$ phase converter [10].

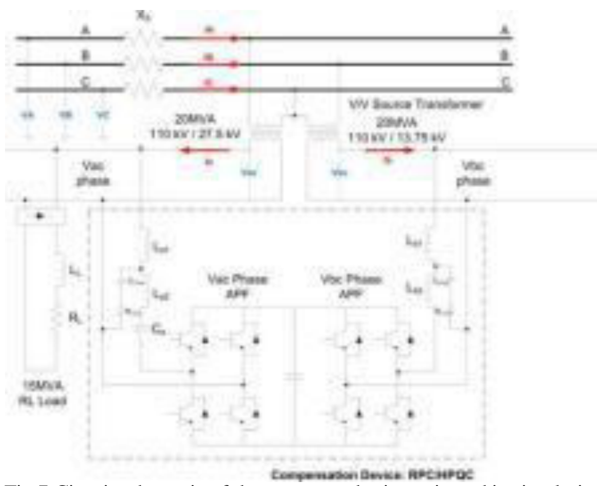


Fig.7.Circuit schematic of the system under investigated in simulation verifications.

Concerning the design of the LC filter parameter, it is selected so as to reduce the harmonics compensation capacity of the compensator. Although the highest load harmonic contents are located at the third harmonic frequency, the LC filter is tuned at the second highest load harmonics (fifth harmonic) for smaller physical size of the components.

## V. ABOUT FUZZY CONTROLLER

The control scheme consists of Fuzzy controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to zero steady error in tracking the reference current signal, Fig. 8 shows the internal structure of the control circuit [11].

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. Firstly, input voltage $V_{dc}$ and the input reference voltage $V_{dc\text{-}ref}$ have been placed of the angular velocity to be the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current $I_{max}$. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in Fig.9.

The fuzzy controller is characterized as follows:
1) Seven fuzzy sets for each input and output;
2) Fuzzification using continuous universe of discourse;
3) Implication using Mamdani's 'min' operator;
4) De-fuzzification using the 'centroid' method.

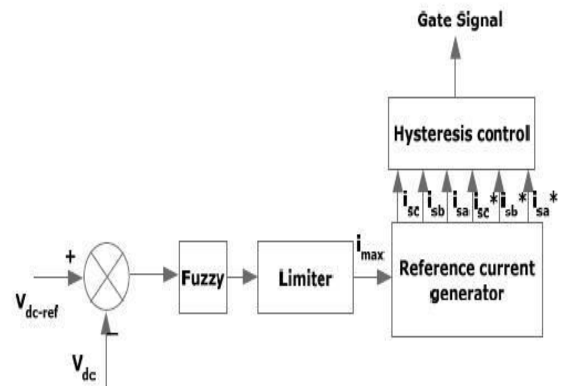



Fig.8.Conventional fuzzy controller

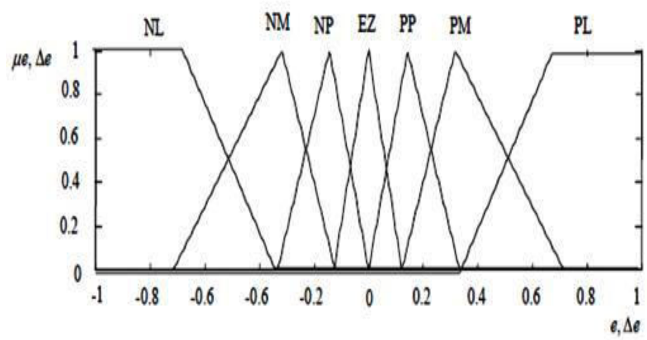



Fig.9. Membership functions for Input, Change in input, Output.

Fuzzification: the process of converting a numerical variable (real number) convert to a linguistic variable (fuzzy number) is called fuzzification.

De-fuzzification: the rules of FLC generate required output in a linguistic variable (Fuzzy Number), according to real world requirements, linguistic variables have to be transformed to crisp output (Real number).

Database: the Database stores the definition of the membership Function required by fuzzifier and defuzzifier.

Rule Base: the elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table 1, with '$V_{dc}$' and '$V_{dc\text{-}ref}$' as inputs.

| $\Delta e$ \ $e$ | NL | NM | NS | EZ | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | NL | NL | NL | NL | NM | NS | EZ |
| NM | NL | NL | NL | NM | NS | EZ | PS |
| NS | NL | NL | NM | NS | EZ | PS | PM |
| EZ | NL | NM | NS | EZ | PS | PM | PL |
| PS | NM | NS | EZ | PS | PM | PL | PL |
| PM | NS | EZ | PS | PM | PL | PL | PL |
| PL | NL | NM | NS | EZ | PS | PM | PL |

## VI. MATLAB/SIMULINK RESULTS

Here the simulation is carried out by different cases are shown in this chapter by using Matlab/simulink software

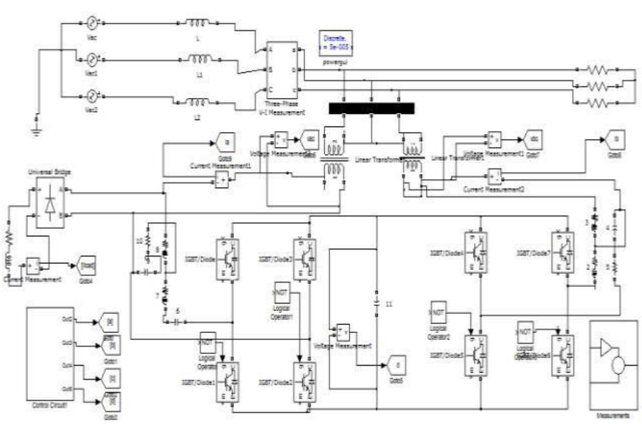
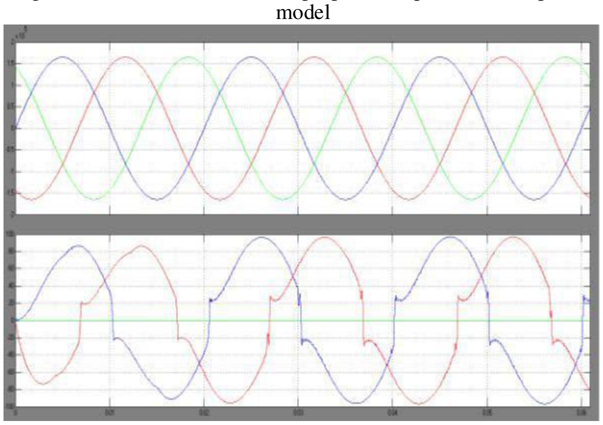
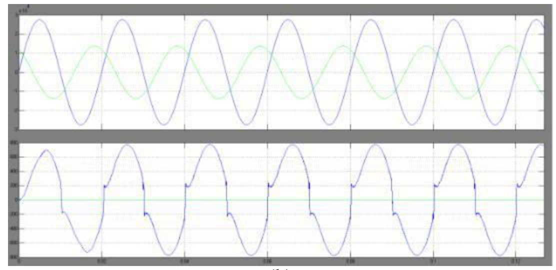


Fig.10 Matlab/simulink model of proposed co-phase traction power model

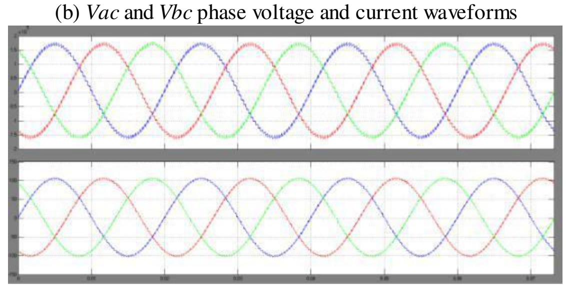


(a)

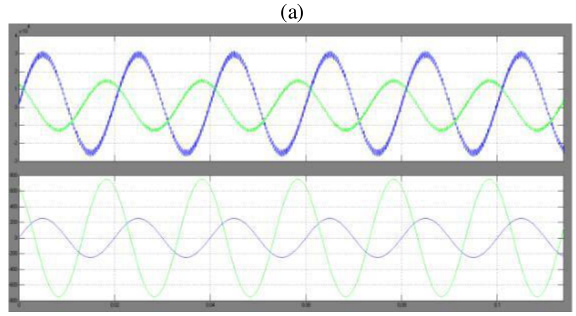


(b)

Fig.11 System performances of the proposed co-phase traction power without compensation (a) Three-phase power source voltage and current waveforms.
(b) *Vac* and *Vbc* phase voltage and current waveforms

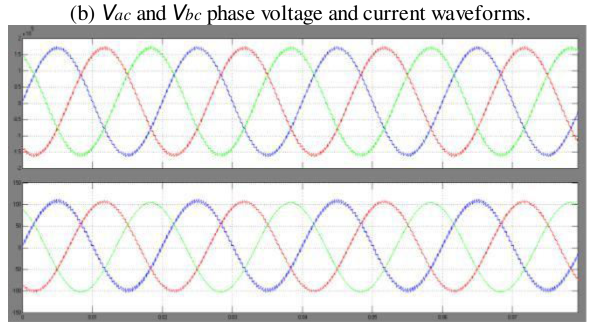


(a)

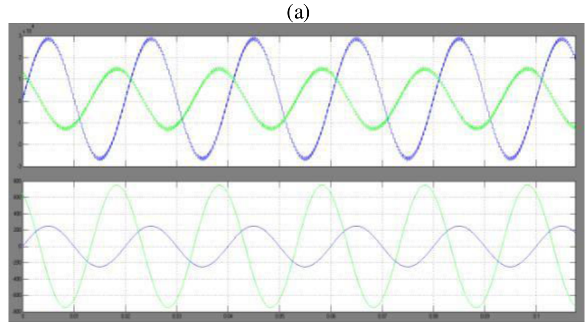


(b)

Fig. 12 System performances of cophase traction power with RPC ($V_{dc}$ = 41 kV). (a) Three-phase power source voltage and current waveforms.
(b) *Vac* and *Vbc* phase voltage and current waveforms.



(a)



(b)

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Fig. 13 System performances of the proposed cophase traction power supply system with HPQC ($V_{dc}$ = 27 kV). (a) Three-phase power source voltage and current waveforms. (b) $V_{ac}$ and $V_{bc}$ phase voltage and current waveforms.

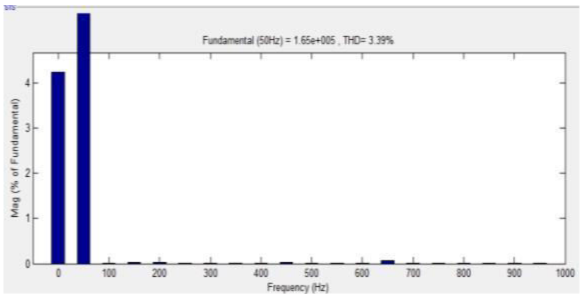
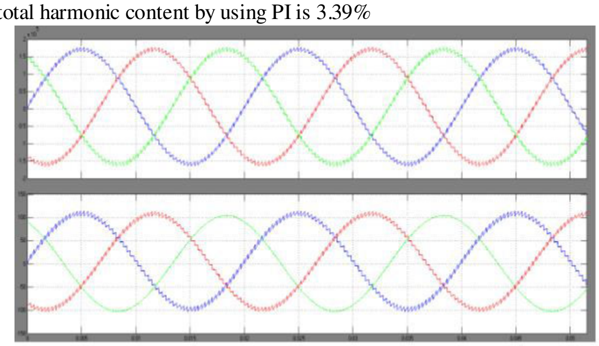
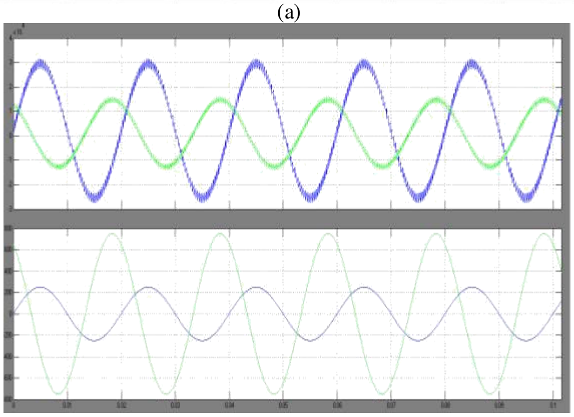



Fig.14 shows the total harmonic content by using PI is 3.39%

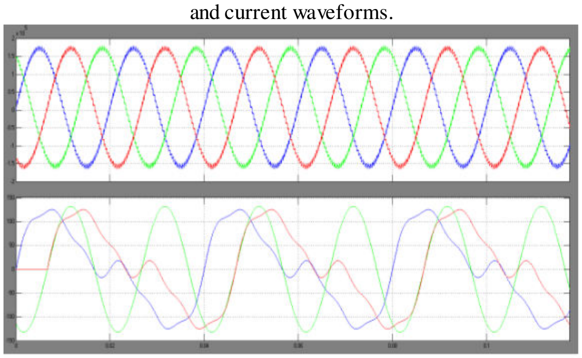


(a)

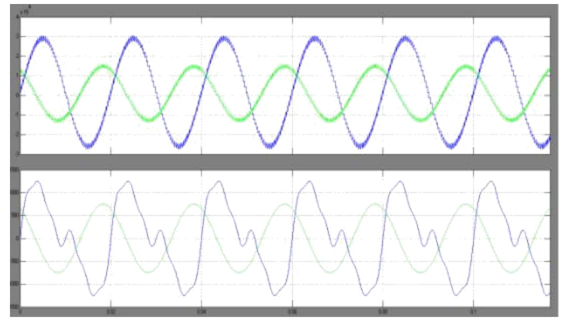


(b)

Fig.15 System performances of the proposed cophase traction power supply system with HPQC ($V_{dc}$ = 41 kV). (a) Three-phase power source voltage and current waveforms. (b) $V_{ac}$ and $V_{bc}$ phase voltage and current waveforms.



(a)



(b)

Fig. 16 System performances of the proposed cophase traction power supply system with HPQC ($V_{dc}$ = 22 kV). (a) Three-phase power source voltage and current waveforms. (b) $V_{ac}$ and $V_{bc}$ phase voltage and current waveforms.

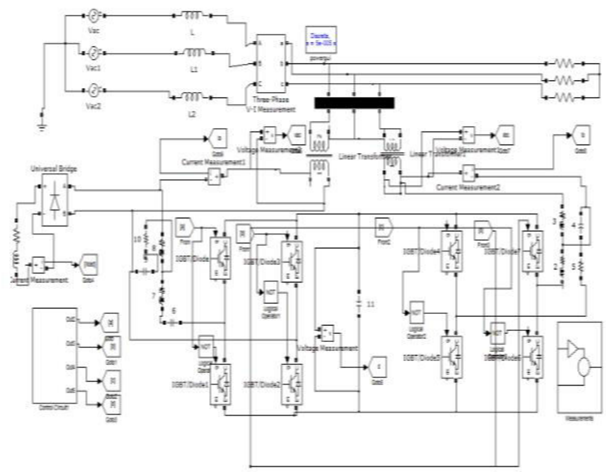


Fig.17 shows the Matlab/simulink model of proposed converter with fuzzy controller

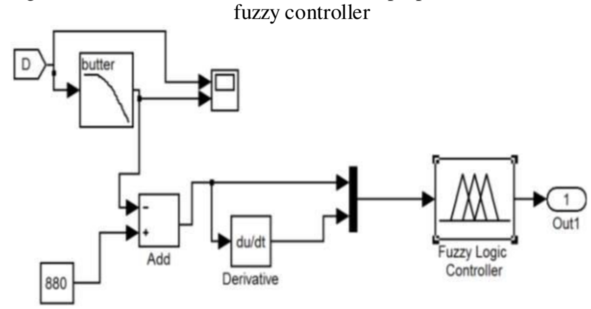



Fig.18 Matlab/simulink model of fuzzy controller connection

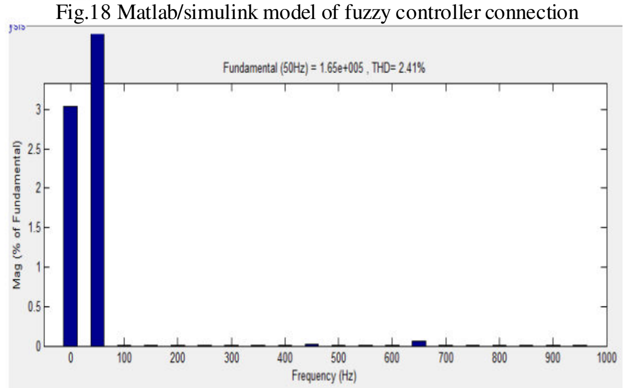



Fig.19 shows the total harmonic content by using fuzzy controller is 2.42%

## VII.CONCLUSION

Flexible AC Transmission System (FACTS) devices become more commonly used as the regulated power supply in various power sectors. So the FACTS devices with control strategy have the potential to significantly improve the stability margin, can also control power flow. This proposed model is implemented using Matlab Simulink software and the obtained resultant waveforms were evaluated and the effectiveness of the system stability and performance of power system have been established. In this concept to reduce the harmonic content in proposed converter by using fuzzy controller in the place of PI controller in this by using PI controller get 3.39% at the same time by using fuzzy controller THD is 2.42%. A HPQC with reduced dc voltage operation compared to conventional RPC during compensation is proposed in this paper. It is found that the minimum HPQC operation voltage rating is dependent only on the traction load PF. PI replace with fuzzy controller to improve the power quality. Finally, all simulations results are verified through Matlab/simulink software.

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