

Optimal DC Voltage Design for High-Speed Traction Power Systems Using LLC-HPQC Control

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Abstract: The economic development of any country depends on the utilization of energy resources. The world's most widely used energy resources being electric energy. Energy being consumed in different forms needs converters and they become very efficient with the invention of power electronic devices. For comprehensive compensation under optimal dc operation voltage in high-speed traction power supplies a hybrid power quality compensator (HPQC) is proposed in this project. Compensation device capacity, power consumptions, and installation Cost can be decreased by reduction in operation voltage of the HPQC. The parameter design procedures for minimum dc voltage operation of HPQC are being explored. It is shown through simulation results that similar compensation performances can be provided by the proposed LLC- HPQC with reduced dc-link voltage level compared to the conventional railway power compensator. A LLC-HPQC is able to afford reactive power, system unbalance, and harmonic compensation in co-phase traction power with reduced operation voltage and without increasing the transformers turns ratio. The co phase traction power supply with proposed HPQC is suitable for high-speed traction applications.

Keywords: Co phase system, power quality compensator, reactive power compensation, traction power, unbalances compensation.

1. Introduction

TRACTION power supply system's usually suffered from different power quality problems. One of the widely applied modes is the single-phase voltage electrified traction load. Due to the fact that traction loads are dynamic and time varying, huge amount of negative sequence current is injected into the three-phase power grid, causing undesired system unbalance. In addition, applications of nonlinear power electronics converters in locomotives also inject significant amount of harmonics into the system. Existence of harmonics and system unbalance in the power system may generate undesired heat loss and cause damage to the system [4]. In addition, due to the fact that most locomotive loadings are inductive, in co phase traction power involving V/V transformer, active power injection is required for system unbalance compensation. This makes the analysis and design different from the traditional hybrid filter.

2. Conventional and Proposed System Configurations

The circuit configuration of the conventional cophase traction power supply with RPC is given in Figure. 1. In this project, 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 (V_{ac} and V_{bc} phases) through V/V transformer. The locomotive loadings are all connected across the same single-phase output (V_{ac}), leaving another phase (V_{bc}) unloaded.

The RPC is composed of one back-to-back converter and is connected across the V_{ac} and V_{bc} phases, so as to provide power quality compensation for the system. The circuit configuration of the proposed cophase traction power supply with HPQC is shown in Fig. 2. In contrast to conventional

structure, the converter is connected to the V_{ac} phase of the transformer via a capacitive coupled hybrid LLC structure. The circuit configuration of the proposed co phase traction power supply with LLC- HPQC is shown in Figure.2. To improve the power conversion efficiency of the Traction power system, A LLC resonant converter employing a Y-connected rectifier is proposed as the isolated ac-dc high-frequency-link power-conversion system. The proposed Y-connected rectifier has the capability to changing the output voltage without increasing the transformer's turn ratio.

The LLC resonant converter is another popular topology because of its outstanding performance such as high-power conversion efficiency, high power density, and over the entire load range. LLC resonant converters have also employing for to reduce the total harmonic distortions and reduce the output ripple current Since an interleaved operation for. The converter is connected to the V_{ac} phase of the transformer via a capacitive coupled hybrid LLC structure. In this paper, a hybrid device combining active and passive compensators, named as the hybrid power quality compensator (HPQC) It can be observed that with capacitive coupled LLC structure, the amplitude of $V_{invaLLC}$ in HPQC can be less than that of V_{invaL} in RPC under the same compensation current. The corresponding mathematical expressions are shown in (1) and (2).

$$|V_{invaL}| = \sqrt{V_{invaLp}^2 + V_{invaLq}^2} = \sqrt{(V_{ac} + |I_{caq}| X_{La})^2 + (|I_{cap}| X_{La})^2} \quad (1)$$

$$|V_{invaLC}| = \sqrt{V_{invaLCp}^2 + V_{invaLCq}^2} = \sqrt{(V_{ac} + |I_{caq}| X_{LCa})^2 + (|I_{cap}| X_{LCa})^2} \quad (2)$$

$$\text{where } |I_{caq}| = I_L \left[\frac{1}{2\sqrt{3}} (\text{PF}) + \sin(\cos^{-1}(\text{PF})) \right] \quad \text{and} \\ |I_{cap}| = I_L \left(\frac{1}{2\text{PF}} \right).$$

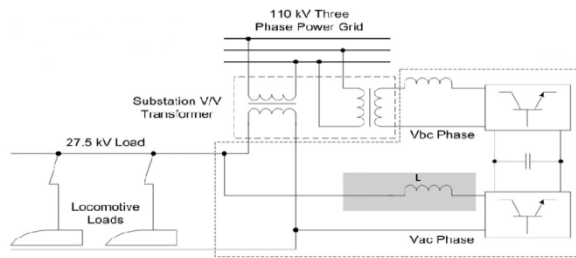


Figure 1: Circuit configuration of the Existing co phase traction power supply system

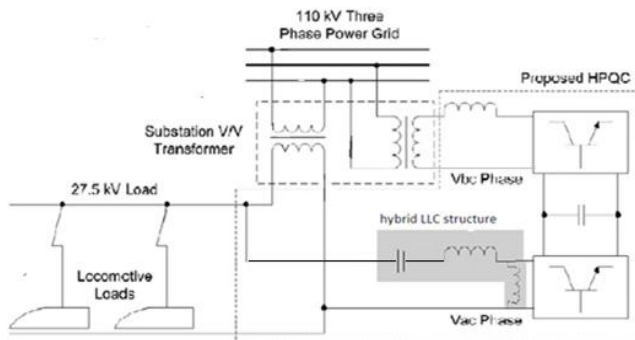


Figure 2: Circuit configuration of the proposed co phase traction power supply with LLC- HPQC

Based on (1) and (2), it can be concluded that with fixed value of V_{ac} , the values of V_{invaL} and V_{invaLC} are highly dependent on the V_{ac} phase coupled impedance. V_{ac} coupled impedance in RPC and HPQC under load PF of 0.85 are shown graphically in Fig. 4. The figure shows clearly that under the examined condition, the value of V_{invaL} in RPC is higher than that of $V_{invaLLC}$ in HPQC.

Figure. 3. Variation of voltage rating with V_{ac} phase coupled impedance in RPC Of the conventional structure and in HPQC of the proposed structure. Moreover, there is a minimum voltage operation point for HPQC. For instance, with load PF of 0.85, the minimum value of $V_{invaLLC}$ in HPQC is approximately 48% of V_{ac} phase voltage.

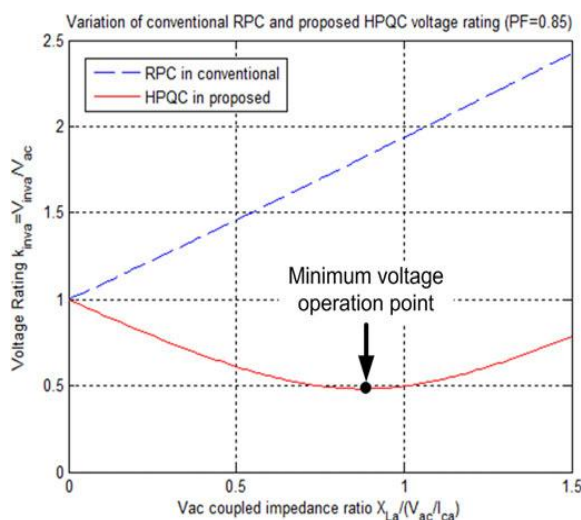


Figure 3: Variation of voltage rating with V_{ac} phase coupled

impedance in RPC of the conventional structure and in HPQC of the proposed structure. The operation point can be

tuned along the curve by Changing the V_{ac} 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.

3. HPQC Parameter Design For The Minimum DC Voltage Operation

The design procedures of V_{ac} and V_{bc} 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 V_{ac} phase converter in HPQC under minimum voltage operation is given in Figure. 4. With constant load PF and capacity, the vector I_{ca} is fixed. Thus, the vector V_{Lca} would vary along the line L_1 as the V_{ac} coupled impedance X_{Lca} varies. It can be observed that the amplitude of $V_{invaLLC}$ can be minimized when it is perpendicular to the vector V_{Lca} .

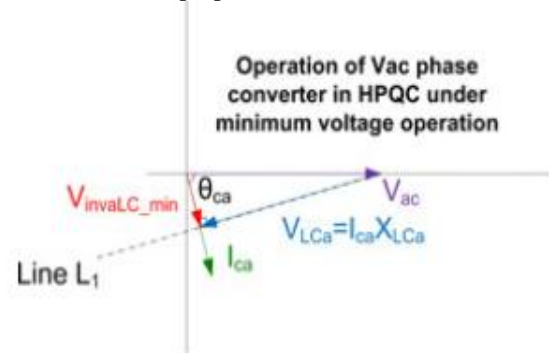


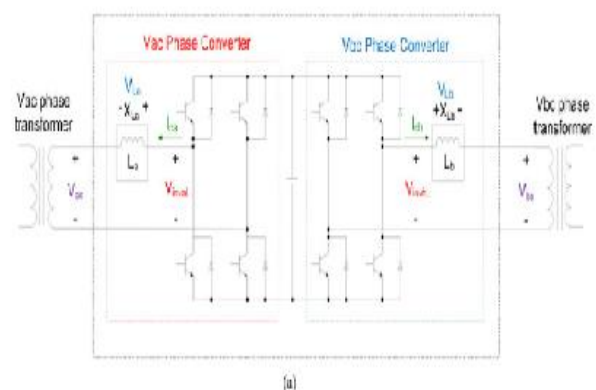
Figure 4: Vector diagram showing the operation of V_{ac} phase.

$$V_{Lca} [V_{invaLC_min}] = I_{ca} X_{Lca} = V_{ac} (\sin \theta_{ca}) \quad (3)$$

The corresponding V_{ac} coupled impedance X_{Lca} required for minimum V_{invaLC} can, thus, be determined as shown in

$$X_{Lca} [V_{invaLC_min}] = \frac{V_{ac} (\sin \theta_{ca})}{I_{ca}} \quad (4)$$

$$X_{Lca} [V_{invaLC_min}] = \frac{V_{ac} (\sin \theta_{ca})}{I_{ca}} = - \left(\frac{\omega^2 L_a C_a - 1}{\omega C_a} \right) \quad (5)$$



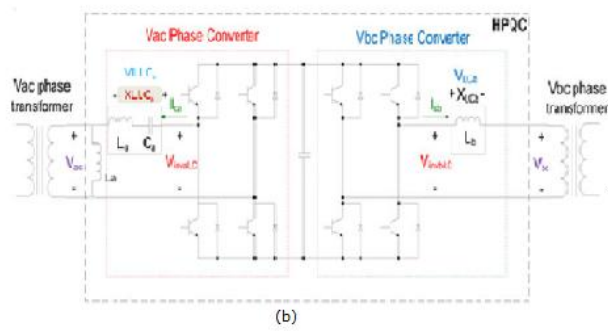


Figure 5: Detailed structure and physical definitions of (a) Existing co phase traction power system and (b) HPQC in the proposed co phase traction power.

The linkage of XL_{Ca} with C_a and L_a can be obtained through circuit analysis, as shown in

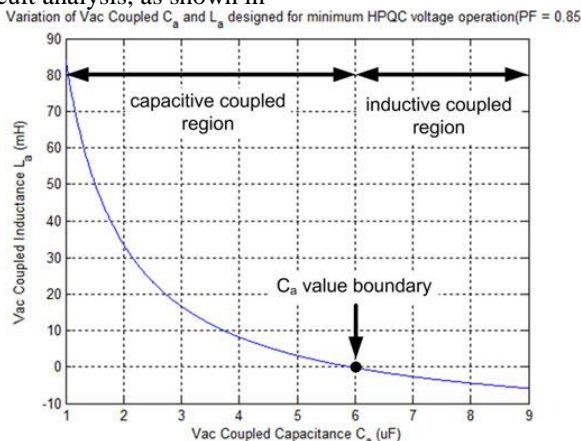


Figure 6: Variation of L_a with C_a for minimum V_{invaLC} (PF = 0.85, 15 MVA).

For example, with V_{ac} of 27.5 kV, load PF of 0.85, and capacity of 15 MVA, the variation of L_a and C_a which satisfies the relationship in (5) is presented in Fig. 6. It can be observed that the relationship between L_a and C_a for minimum HPQC voltage rating is nonlinear. Minimum voltage operation in HPQC, thus, fails when the value of C_a is outside this boundary.

B. Vbc Phase Coupled Impedance Design

For the V_{bc} phase coupled impedance design it is determined with matching to the minimum voltage V_{invaLC} correspondence with the $V_{invaLCmin}$. The minimum HPQC voltage is represented by the circle C_{ira} with radius $V_{invaLCmin}$. Assuming constant load PF and capacity, the vector V_{LCb} varies along the line L_2 with varying V_{bc} phase coupled impedance XL_{Cb} . Two intersection points (pt.1 and pt.2) are present between the circle C_{ira} and the line L_2 . These two points are the operation points which satisfy the voltage matching with $V_{invaLCmin}$. They may be determined mathematically. The mathematical expression showing the intersection of circle C_{ira} with radius V_{invaLC}

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

$$(pt.2) \frac{V_{bc} \cos \theta_{cb} - \sqrt{V_{invaLCmin}^2 - V_{bc}^2 \sin^2 \theta_{cb}}}{I_{cb}} = X_{LCb}$$

$$= \frac{V_{bc} \cos \theta_{cb} + \sqrt{V_{invaLCmin}^2 - V_{bc}^2 \sin^2 \theta_{cb}}}{I_{cb}} \quad (pt.1) \quad (7)$$

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

$$V_{bc} \leq \frac{V_{invaLCmin}}{\sin \theta_{cb}} \quad (8)$$

C. Minimum HPQC Voltage Rating Achievable

After investigations of the V_{ac} and V_{bc} phase coupled impedance design for the minimum HPQC operation voltage,

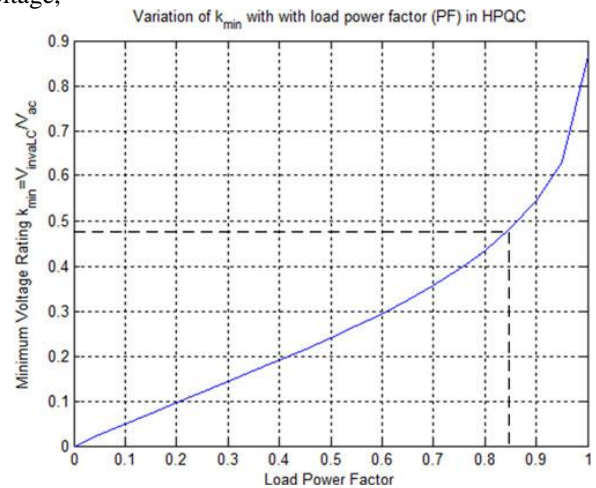


Figure 7: The curve showing the variation of minimum HPQC voltage rating (k_{min}) against load PF

By substituting the design of V_{ac} coupled impedance XL_{Ca} in (4) into the HPQC V_{invaLC} voltage calculation in (2), the minimum value of V_{invaLC} in HPQC ($V_{invaLCmin}$) can be obtained

$$V_{invaLCmin} = (\cos \theta_{ca}) V_{ac} \quad (9)$$

Neglecting the effect of V_{ac} phase voltage, the minimum HPQC voltage rating is determined by

$$k_{min} = \frac{V_{invaLCmin}}{V_{ac}} = \cos \theta_{ca} \quad (10)$$

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

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

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 V_{ac} phase voltage of 27.5 kV, the minimum value of V_{invaLC} achievable is, thus, 13.2 kV. The peak value of the V_{ac} phase voltage is 38.89

kV, and the minimum HPQC dc-link voltage required is $\sqrt{2}$ times of $V_{invaLLC}$, which is approximately 18.67 kV.

4. Control Philosophy

The control block of the system is shown in Figure. 8. The instantaneous load active and reactive power is computed using the modified instantaneous pq theory. The

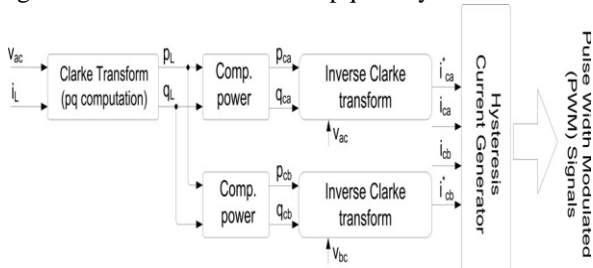


Figure 8: Control block diagram of the HPQC for cophase traction power supply compensation

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

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} v_{ac} \cdot i_L + v_{acd} \cdot i_{Ld} \\ v_{acd} \cdot i_L - v_{ac} \cdot i_{Ld} \end{bmatrix} \quad (12)$$

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

$$p_L = p_{dc} + p_{ac} \quad (13)$$

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 V_{ac} phase converter, while p_{cb} and q_{cb} are the required active and reactive compensation power from the V_{bc} phase converter

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} p_{dc} + p_{ac} \\ \frac{1}{2\sqrt{3}} p_{dc} + q \\ -\frac{1}{2} p_{dc} \\ -\frac{1}{2\sqrt{3}} p_{dc} \end{bmatrix} \quad (14)$$

$$i_{ca}^* = \frac{1}{v_{ac}^2 + v_{acd}^2} \begin{bmatrix} v_{ac} & v_{acd} \end{bmatrix} \begin{bmatrix} p_{ca} \\ q_{ca} \end{bmatrix} \quad (15)$$

$$i_{cb}^* = \frac{1}{v_{bc}^2 + v_{bcd}^2} \begin{bmatrix} v_{bc} & v_{bcd} \end{bmatrix} \begin{bmatrix} p_{cb} \\ q_{cb} \end{bmatrix} \quad (16)$$

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} .

5. Simulation Circuit

Simulations using MATLAB are done to verify the aforementioned theoretical studies. The circuit schematic of the system used in simulations is provided in Figure.9 The substation V/V transformer is composed of two 20 MVA single-phase transformers, with turning ratios of 110 kV/27.5 kV and 110 kV/13.75 kV. Traction loads are simulated using rectifier RL load, with linear capacity of 15 MVA. The compensation device is then connected across the two single-phase outputs of V/V transformer to provide power quality compensation of the system. Notice that the LCL filter is included here to filter the ripples introduced by the compensator.

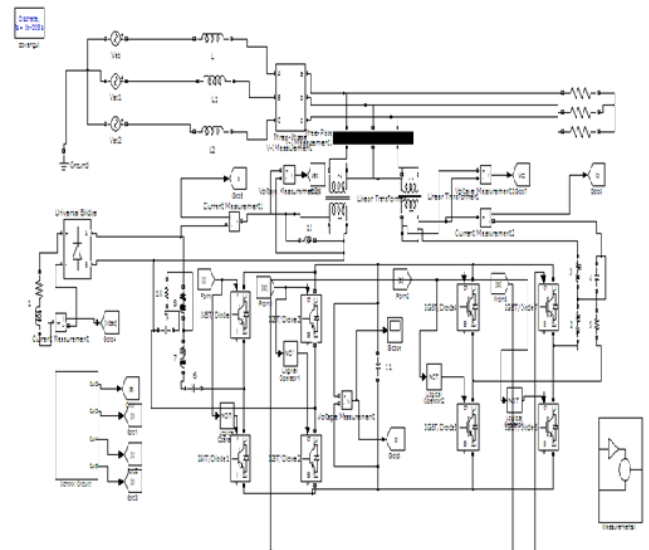
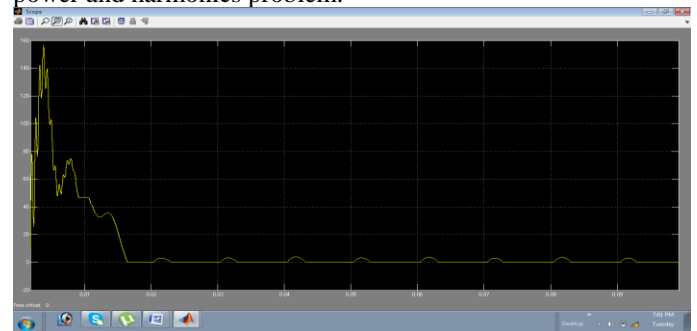


Figure 9: Proposed Co phase Traction Power Supply System With HPQC

6. Simulation Results

A. Cophase Traction Power without Compensation

The system performance without compensation is investigated first. Shown in Figure. 10 are the three-phase source, secondary voltage, and current waveforms for cophase traction power without compensation. It could be observed that the system suffers from unbalance, reactive power and harmonics problem.



(a)

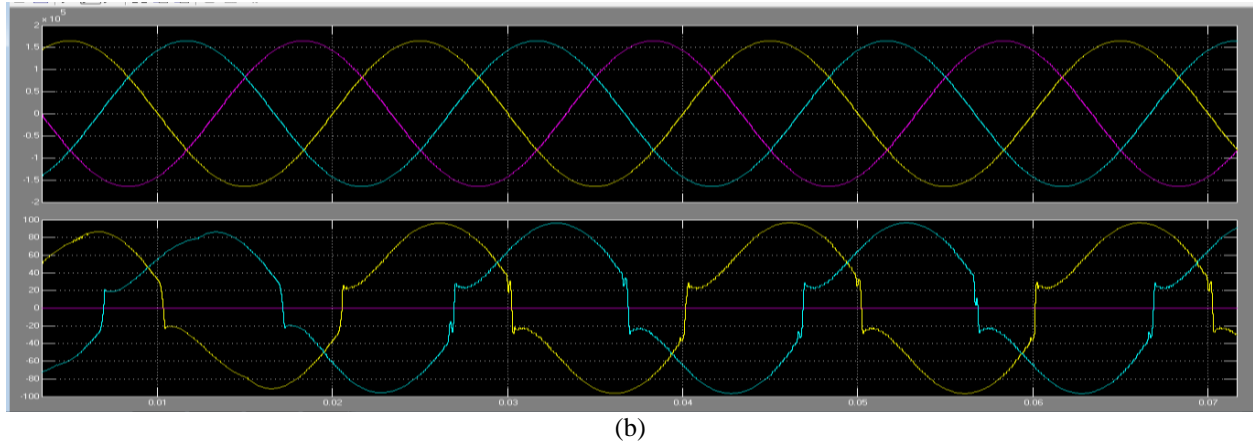


Figure 10: proposed co phase traction power without compensation.(a) load side output voltage (b)Three-phase power source voltage and current waveforms.

Table 1: Existing System Circuit Parameters Use in the Simulation Verifications

No.	Items	Description
1	Vac Coupling Inductance 1 L_{a1}	3.4 mH
2	Vac Coupling Inductance 2 L_{a2}	3.4 mH
3	Vac LCL Capacitance C_{LCLa}	5 uF
4	Vac LCL Damped Resistance R_{LCLa}	20 ohm
5	DC Link Capacitance C_{dc}	10000 uF
6	Vbc Coupling Inductance 1 L_{b1}	4 mH
7	Vbc Coupling Inductance 2 L_{b2}	4 mH
8	Vbc LCL Capacitance C_{LCLb}	5.63 uF
9	Vbc LCL Damped Resistance R_{LCLb}	20 ohm

may thus be concluded that under the simulated conditions, the optimum dc-link voltage of the proposed HPQC is 27 kV.

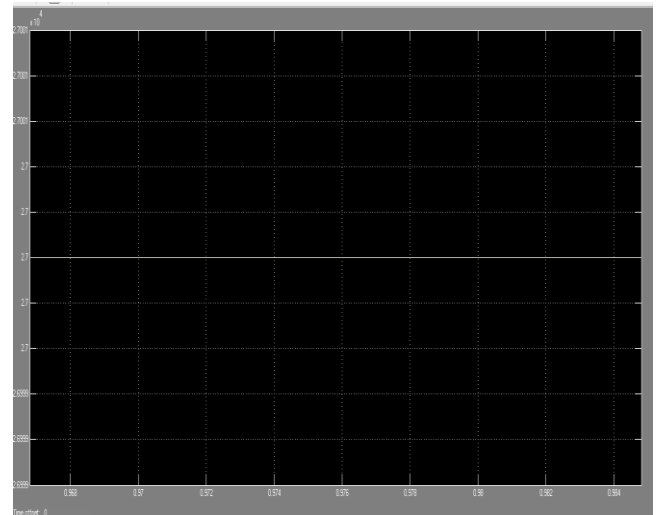
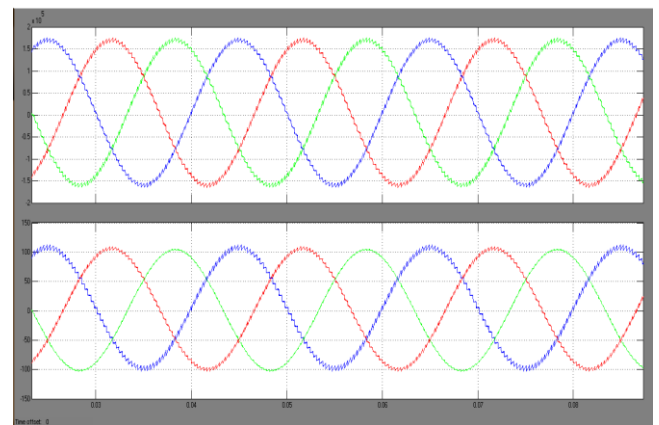


Table 2: HPQC Circuit Parameters Used InThe Simulation Verifications

NO.	Items	Description
1	Vac coupling inductance 1 L_{a1}	3.4mh
2	Vac coupling inductance 2 L_{a2}	3.4mh
3	Vac coupling inductance 3 L_{a3}	3.4mh
4	Vac coupling Capacitance C_a	60μF
5	Vac LCL Capacitance C_{LCLa}	5μF
6	Vac LCL Damped resistance R_{LCLa}	20ohm
7	DC link capacitance C_{dc}	10000μF
8	Vbc coupling inductance 1 L_{b1}	4mh
9	Vbc coupling inductance 2 L_{b2}	4mh
10	Vbc LCL Capacitance C_{LCLb}	5.63μF
11	Vbc LCL Damped resistance R_{LCLb}	20ohm

B. Cophase Traction Power With Proposed HPQC (Vdc =27 kV)

The HPQC circuit parameters used in the simulations are presented in Table II. The simulated load PF is around 0.94. According to the investigations, the minimum HPQC voltage rating k_{min} is 0.61. With traction load electrified by 27.5 kV, the minimum value of V_{invaLC} in HPQC is 16.78 kV. The dc-link voltage of HPQC used in the simulation is 27 kV. It can be observed that with dc-link voltage lower than 27 kV in the proposed HPQC, the compensation performances become worse. The source current THD and unbalance are both above standard. On the other hand, when the dc-link voltage is above 27 kV, the compensation performance is more or less the same as that using 27 kV. It



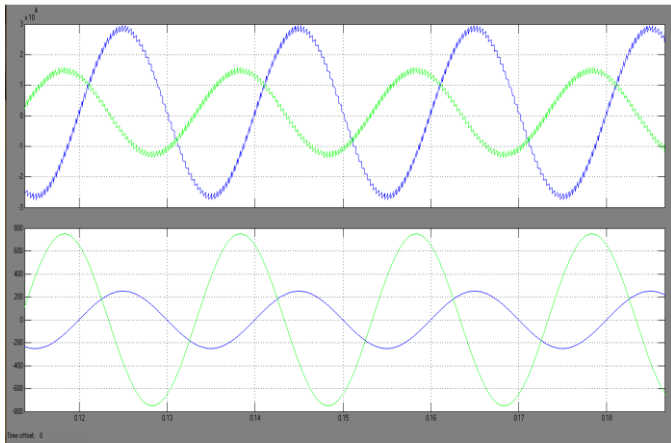


Figure 12: System performances of the proposed cophase traction power supply system with HPQC ($V_{dc} = 27$ kV). (a) Load side output voltage for HPQC ($v_{dc}=27kv$) (b) Three-phase power source voltage and current waveforms. (c) V_{ac} and V_{bc} phase voltage and current waveforms

Table 3: Summarized System Statistics in Simulation

	Three phase source					
	Existing system compensating ($V_{dc}=27kv$)			Proposed system HPQC ($V_{dc}=27kv$)		
	A	B	C	A	B	C
Current THD(%)	2.91	2.90	2.91	1.68	2.17	1.90
Power factor	0.90	0.90	0.90	0.98	0.98	0.98
Current unbalance (%)	7.54			5.57		

7. Conclusion

A LLC-HPQC with reduced dc voltage operation compared to Existing System during compensation is proposed in this project. The parameter design for the minimum HPQC voltage operation is being discussed. It is found that the minimum HPQC operation voltage rating is dependent only on the traction load PF. It increases with increasing load PF. For instance, with load PF of 0.85, the minimum HPQC voltage rating is only 0.48. It is also verified through simulation that the LLC-HPQC would operate at the minimum voltage with the proposed parameter design, and without increasing the transformer turn's ratio, thus to reach the good power factor at a certain dc link voltage. HPQC would operate at the minimum voltage with the proposed parameter design, the proposed system voltage operation point is lower than that of conventional System. It can be observed that with dc-link voltage lower than 27 kV in the proposed HPQC, the compensation performances become worse. The source current THD and unbalance are both above standard. On the other hand, when the dc-link voltage is above 27 kV, the compensation performance is more or less the same as that using 27 kV. It may thus be concluded that under the simulated conditions, the optimum dc-link voltage of the proposed HPQC is 27 kV. In this project the fuzzy logic controller is used, though the fuzzy logic controller give fast response the accuracy may be slightly

lesser. In future we can replace fuzzy logic controller with Hybrid Neuro Fuzzy controller to improve the accuracy as well as response of the system.

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