

Conventional DC Voltage Operating System for High Speed Traction Power Supplies Using LLC-HPQC Control

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ABSTRACT

In this paper a hybrid power quality compensator (HPQC) is proposed for compensation in cophase traction power supply and minimum dc operation voltage is achievable for high-speed traction power supply. The parameter design procedure for minimum dc operation voltage in HPQC as well as minimum voltage rating with load PF is discussed. The detailed discussions of proposed circuit configurations of HPQC are provided in section II, together with comparison with conventional RPC. In comparison with conventional railway power compensator proposed HPQC can achieve reduced dc link voltage level. It is also verified through simulations results that the LLC-HPQC would operate at the minimum voltage with the proposed parameter design. HPQC is able to provide system unbalances, reactive power, and harmonic compensation in cophase traction power with reduced operation voltage. The cophase traction power supply with proposed HPQC is suitable for high-speed traction applications.

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1. INTRODUCTION

In electrified railway systems railway locomotives are treated as single-phase loads, the speed and load condition of the train always changes frequently, which can cause the low power factor, high contents of harmonic currents, and negative-sequence currents in traction power systems. Conventional passive power quality compensators, such as reactive power compensation capacitors and passive filters, are single-phase equipment and are installed in each feeder of a traction substation separately. Usually, the coupling factor between two feeders is neglected due to the independent operation of each passive compensator. Moreover, passive equipment cannot adjust the capability flexibly, where over- and under-compensation occur frequently due to the frequently changed load.

Cophase traction power supply system is one of the newly proposed traction power systems which solve the problem of excessive neutral sections installation in traction power supplies. Elimination of neutral sections may reduce the velocity loss of the locomotives, and cophase traction power thus has high potential as high-speed traction power supply system. Locomotive loads are connected across the same single-phase output to avoid risk of phase mixing. The compensation device (such as RPC) is then connected into the system to provide system power quality compensation

In this project, a hybrid device combining active and passive compensators, named as the hybrid power quality compensator (HPQC), is proposed for compensation in cophase traction power supply. The parameter design procedure for minimum HPQC voltage operation as well as the minimum voltage rating achievable is discussed. Descriptions of proposed circuit configurations of cophase traction power with

HPQC are together with comparisons with conventional RPC. The parameter design for the minimum HPQC voltage operation and the minimum operation voltage achievable is investigated.

2. CONVENTIONAL AND PROPOSED SYSTEM CONFIGURATION

The structure of RPC with three-phase V/V transformers is depicted in Figure 1. The 220-kV three-phase high-voltage source is converted into two 27.5-kV single-phase voltage sources, which are connected to the two feeder sections, via a three-phase V/V traction transformer. The turn's ratio of the V/V traction transformer is K_v . The RPC, consisting of two converters that are connected back to back through a common dc capacitor with a stable dc-link voltage, is connected to the two feeder sections via two step down transformers with a turns ratio of K_D . The two converters are connected to the single phase step down transformers via output inductors L_a and L_b respectively. The two converters can be controlled as current sources to shift a certain amount of active power from one feeder section to the other. These two converters can also provide harmonic suppression and reactive power compensation. Hence, the system can achieve integrated compensation of negative-sequence currents, harmonic currents, and reactive power.

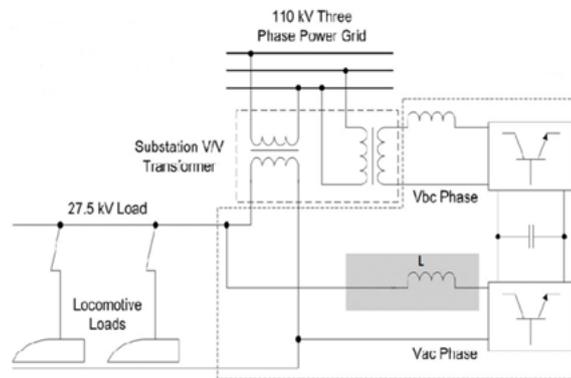


Figure 1. Circuit Configuration of the Existing Co Phase Traction Power Supply System

In Figure 2 the circuit configuration of the proposed cophase traction Power supply with LLC-HPQC is shown. In contrast to Conventional structure, the converter is connected to the V_{ac} phase of the transformer via a capacitive coupled hybrid LLC structure. As will be discussed later, this results in the reduction of converter dc bus voltage of HPQC. 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 Figure 4.

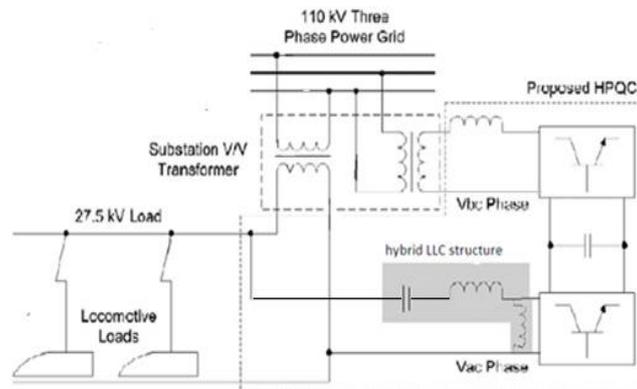


Figure 2. Circuit Configuration of the Proposed Co Phase Traction Power Supply with LLC-HPQC

Since traction loads are mostly inductive, the following contents are discussed based on the assumption of inductive loadings. The vector diagrams of the V_{ac} phase converter for the conventional RPC and proposed HPQC are shown in Figure 3. It can be observed that with capacitive coupled LLC structure, the amplitude of $V_{invaLLC}$ in HPQC can be less than that of V_{invaLL} in RPC under the same compensation current. The corresponding mathematical expressions are shown in (1) and (2)

$$\begin{aligned}
 |V_{invaL}| &= \sqrt{V_{invaLp}^2 + V_{invaLq}^2} \\
 &= \sqrt{(V_{ac} + |I_{caq}|X_{La})^2 + (|I_{cap}|X_{La})^2}
 \end{aligned} \tag{1}$$

$$\begin{aligned}
 |V_{invaLLC}| &= \sqrt{V_{invaLLCp}^2 + V_{invaLLCq}^2} \\
 &= \sqrt{(V_{ac} + |I_{caq}|X_{LLCa})^2 + (|I_{cap}|X_{LLCa})^2}
 \end{aligned} \tag{2}$$

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

$$|I_{cap}| = I_L \left(\frac{1}{2PF} \right)$$

Since the high speed railway locomotives are often driven by four quadrant PWM converters the power factor of two feeder sections is nearly 1. In Figure 2, $V_{invaLLC}$ Posses a U or V shaped surface specifying minimum voltage operating point with HPQC. Compare to that in RPC the value is less than 1 indicating that the required amplitude of converter is less than that of main supply. The vector diagram showing the operation of V_{ac} phase converter in HPQC and RPC comparison is shown below in Figure 3.

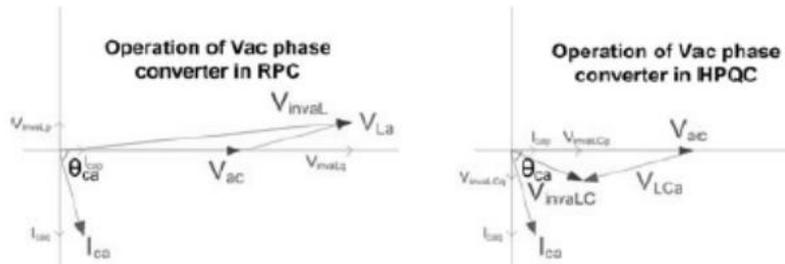


Figure 3. Vector Diagram Showing the Operation of V_{ac} Phase Converter in (a) RPC of the Conventional Structure and (b) HPQC of the Proposed Structure

From (1) and (2) it can be concluded that the values of V_{invaL} and $V_{invaLLC}$ are dependent on the phase impedance of V_a and V_b phases

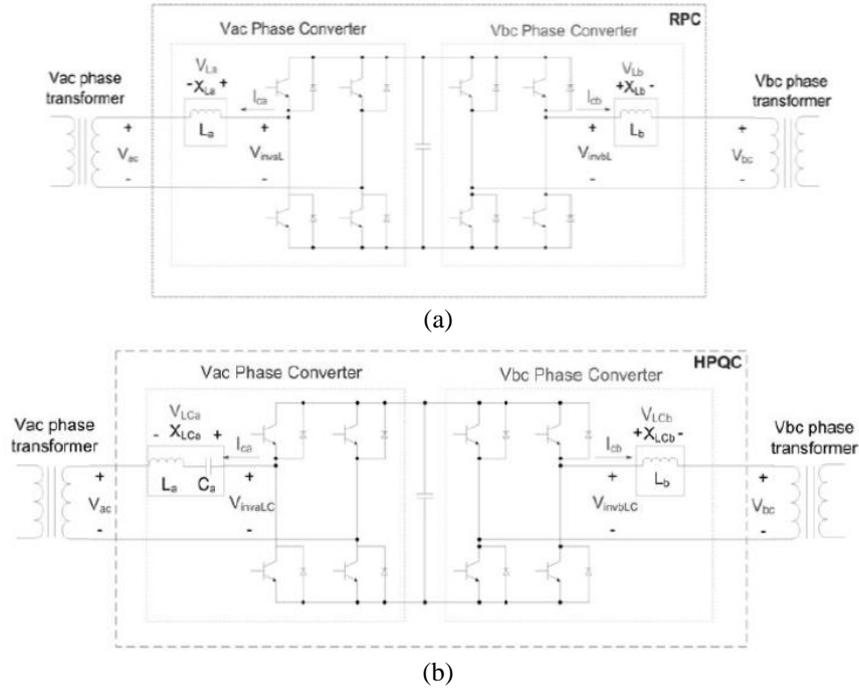


Figure 4. Detailed Structure and Physical Definitions of (a) Existing System Used in High Speed Traction (b) Proposed System of HPQC in Cophase Traction

3. PARAMETER DESIGN PROCEDURE FOR MINIMUM DC VOLTAGE OPERATION OF HPQC

The design procedure of phase coupled impedances of V_{ac} and V_{bc} phases are explained in this section and also the investigation of minimum dc voltage operation of HPQC is achieved. With load PF of 0.85 the minimum value of $V_{invaLLC}$ in HPQC is approximately 48% of V_{ac} phase voltage. The operating point can be tuned along the curve by changing the V_{ac} coupled impedance. Therefore the operation of HPQC is located at minimum voltage operation point via specific parameter design is shown in Figure 5.

3.1. Phase Coupled Impedance Design V_{ac}

The vector diagram showing the operation of V_{ac} phase converter in HPQC under minimum voltage operation is given in Figure 6. The minimum amplitude of $V_{invaLLC}$ occurs when the compensation current I_{ca} is in phase with the voltage $V_{invaLLC}$ for further calculation of power angle as θ_{ca} . The mathematical relation can be derived from the Figure.6.

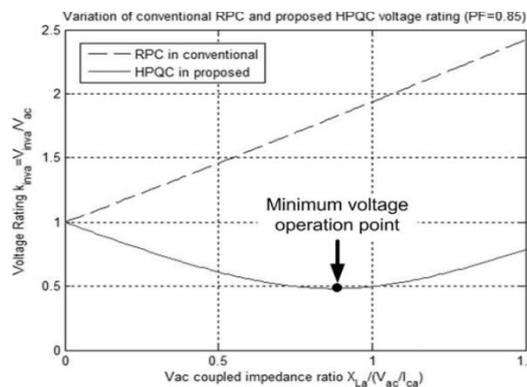


Figure 6. Vector Diagram Showing the Operation of V_{ac}

$$V_{LLCa} [V_{invaLLC_min}] = I_{ca} X_{LLCa} = V_{ac} (\sin \theta_{ca}) \tag{3}$$

The corresponding phase coupled impedance X_{LLCa} required for minimum $V_{invaLLC}$ is determined as

$$X_{LLCa} [V_{invaLLC_min}] = \frac{V_{ac} (\sin \theta_{ca})}{I_{ca}} \tag{4}$$

The ultimate goal of parameter design is to determine the V_{ac} phase coupled inductance L_a and capacitance C_a for practical applications. The linkage of X_{LLCa} with C_a and L_a can be obtained through circuit analysis and the equation is

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

The variation of L_a and C_a with capacity of 15MVA, V_{ac} of 27.5KV and load PF of 0.85 satisfies the relationship which is presented in Figure 7.

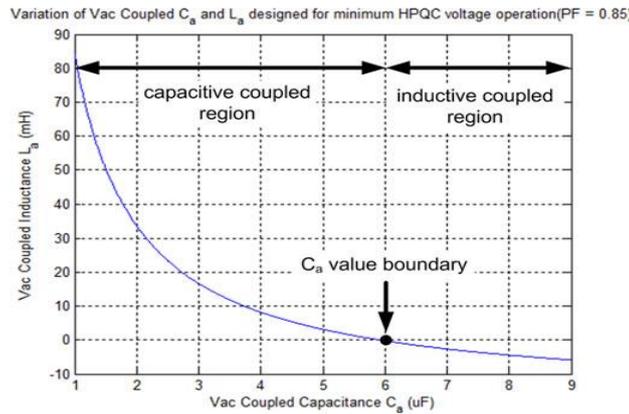


Figure 7. Variation of L_a with C_a for Minimum dc Voltage Operation

From this Figure we can observe that the relationship between L_a and C_a for minimum HPQC voltage is non-linear if the value of C_a exceeds the boundary causing the operation similar to RPC.

3.2. Phase Coupled Impedance Design V_{bc} .

The vector diagram showing the operation of V_{bc} phase converter in HPQC in correspondence with the $V_{invaLLC-min}$ is shown in Figure 8.

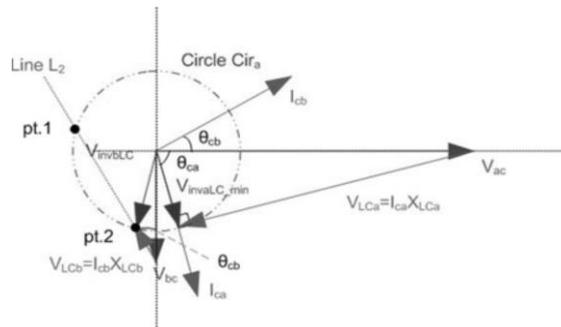


Figure 8. Vector DIAGRAM SHOWING the Operation of HPQC with Minimum dc Voltage

Assuming constant load PF and capacity the vector V_{LLCb} varies along with the line L_2 with varying phase coupled impedance X_{LLCb} . Two intersection points between the circle and the line L_2 represents the operation points which satisfy the voltage matching with $V_{invaLLC-min}$. The mathematical expression showing the intersection of circle and the line L_2 is given as

$$V_{invaLLC_min}^2 = \left(V_{LLCb}^2 \sin^2 \theta_{cb} + (V_{bc} - V_{LLCb} \cos \theta_{cb})^2 \right) \quad (6)$$

Although both point 1 and point 2 may satisfy the voltage matching with minimum dc voltage of HPQC operation point 2 is preferred due to the low impedance of X_{LLCb} and lower power consumptions

3.3. Minimum Voltage Operation of HPQC Against Load Power Factor

The value of $V_{invaLLC-min}$ is a key factor for determining the minimum HPQC operation voltage. The minimum value of $V_{invaLLC}$ in HPQC $V_{invaLLC-min}$ can be obtained as

$$V_{invaLLC_min} = (\cos \theta_{ca}) V_{ac} \quad (7)$$

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

$$K_{min} = \frac{V_{invaLLC_min}}{V_{ac}} = \cos \theta_{ca} \quad (8)$$

It is now obvious that the minimum HPQC voltage rating is dependent only on the power angle of I_{ca} . The expression for load power factor is

$$\theta_{ca} = \tan^{-1} \left(\frac{\frac{1}{2\sqrt{3}} PF + \sin(\cos^{-1}(PF))}{\frac{1}{2} PF} \right) \quad (9)$$

The graph showing the variation of minimum HPQC voltage rating (K_{min}) against load power factor is plotted in Figure 9.

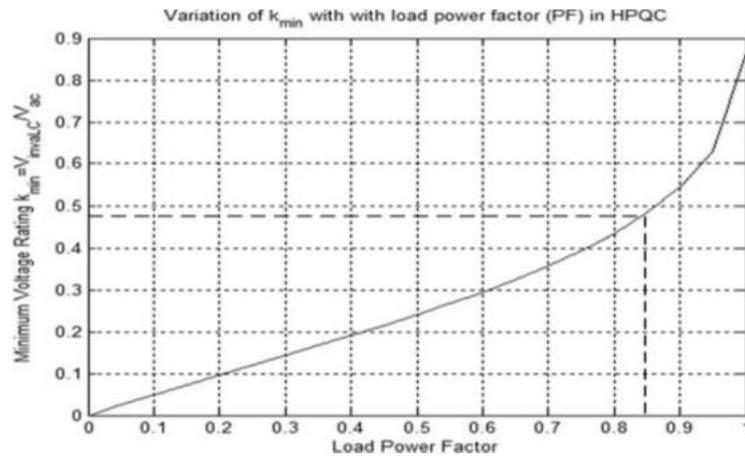


Figure 9. Graph Showing the Variation of HPQC Minimum Voltage with Load PF

4. CONTROL THEORY

The control block diagram of the proposed HPQC for cophase traction power supply is shown in Figure 10. The theories of active and reactive power are calculated using modified instantaneous p-q theories.

The expression for active and reactive powers is shown in (10), 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

$$\begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} v_{ac} \cdot i_L + v_{acd} \cdot i_{Ld} \\ v_{acd} \cdot i_L - v_{ac} \cdot i_{Ld} \end{bmatrix} \tag{10}$$

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. The mathematical expression is shown in

$$P_L = P_{dc} + P_{ac} \tag{11}$$

The required compensating power is then computed according to the power quality requirement, as expressed in (12), 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

$$\begin{bmatrix} p_{ca} \\ q_{ca} \\ p_{cb} \\ q_{cb} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} P_{dc} + P_{ac} \\ \frac{1}{2\sqrt{3}} P_{dc} + q \\ -\frac{1}{2} P_{dc} \\ -\frac{1}{2\sqrt{3}} P_{dc} \end{bmatrix} \tag{12}$$

The reference phase compensation currents i_{ca}^* and i_{cb}^* are calculated by using the equations (13) and (14)

$$i_{ca}^* = \frac{1}{v_{ac}^2 + v_{acd}^2} [v_{ac} \ v_{acd}] \begin{bmatrix} p_{ca} \\ q_{ca} \end{bmatrix} \tag{13}$$

$$i_{cb}^* = \frac{1}{v_{bc}^2 + v_{bcd}^2} [v_{bac} \ v_{bacd}] \begin{bmatrix} p_{cb} \\ q_{cb} \end{bmatrix} \tag{14}$$

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

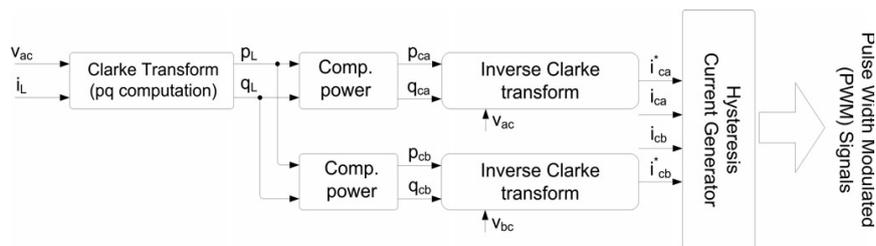


Figure 10. Control block diagram of the HPQC for cophase traction power supply compensation

5. SIMULATION VERIFICATIONS

Simulations are performed using MATLAB to verify the above theoretical studies. The schematic circuit diagram of the proposed HPQC for high speed traction is provided in Figure 11. 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.

5.1. Cophase Traction Power Without Compensation

The system performance without compensation is verified first. Shown in Figure12 are the three-phase source, secondary voltage, and current waveforms for cophase traction power without compensation. From Figure 12 we conclude that system suffers from unbalance, reactive power and harmonics problem.

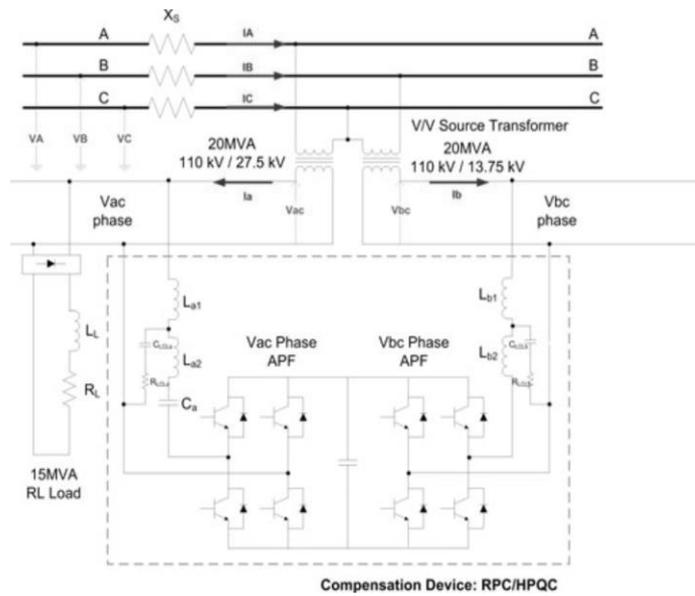


Figure 11. Circuit Schematic of the System under Investigated in Simulation Verifications

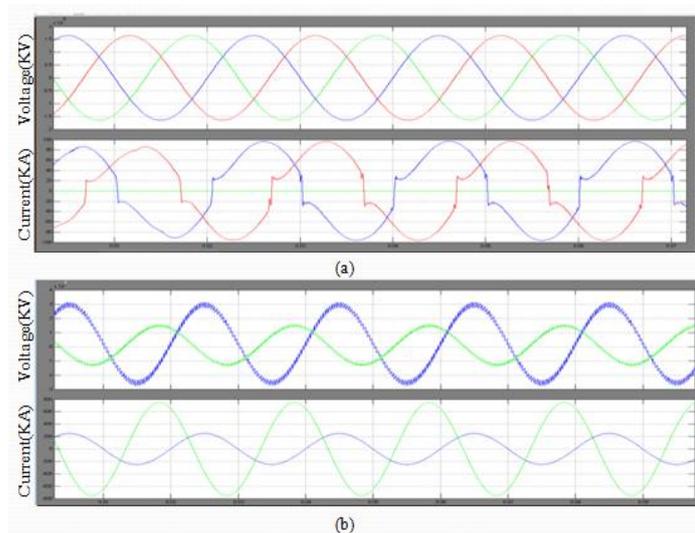


Figure12. System performances of the proposed cophase traction power without compensation. (a) Three-phase power source voltage and current waveforms. (b) V_{ac} and V_{bc} phase voltage and current waveforms.

Table 1. Rpc Circuit Parameters Used in 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 μ F |
| 4 | Vac LCL Damped Resistance R_{LCLa} | 20 ohm |
| 5 | DC Link Capacitance C_{dc} | 10000 μ F |
| 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 μ F |
| 9 | Vbc LCL Damped Resistance R_{LCLb} | 20 ohm |

5.2. Cophase traction power with conventional RPC ($V_{dc}=41$ KV)

Now simulation is performed on cophase traction power with RPC to examine the compensation performance. The RPC circuit parameters are shown in Table 1. Beside C_a the other values are chosen according to the parameter design in Section III. As per the requirement of designed RPC the dc-link voltage is selected slightly higher than the peak voltage of V_{ac} phase.

5.3. Cophase Traction Power with Proposed HPQC ($V_{dc}=27$ KV)

The HPQC circuit parameters used in the simulations is presented in Table 2. Since the load harmonics are mostly concentrated at 3rd and 5th fundamental harmonics the values of coupling inductance and capacitance are selected based on the 5th harmonics.

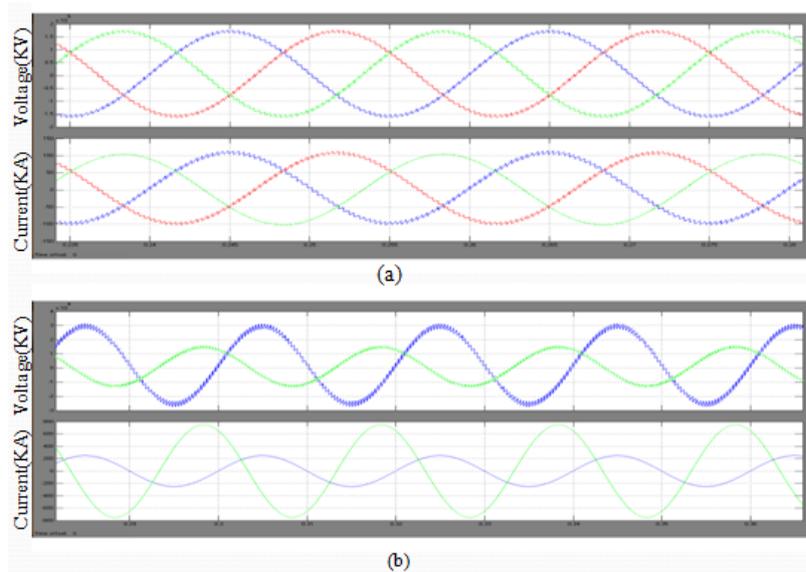


Figure 13. System performances of cophase traction power with RPC ($V_{dc}=41$ kV).(a)Three-phase power source voltage and current waveforms.(b) V_{ac} and V_{bc} phase voltage and current waveforms

The simulated load PF is around 0.94. As per our examination, the minimum HPQC voltage rating K_{min} is 0.61. With traction load electrified by 27.5 kV, the minimum value of $V_{invalLLC}$ in HPQC is 16.78 kV. The dc-link voltage of HPQC used in the simulation is 27 kV. Simulation waveforms are shown in figure 14. 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.

Table 2. Hpqc Circuit Parameters Used 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 Coupling Capacitance C_a | 60 uF |
| 4 | Vac LCL Capacitance C_{LCLa} | 5 uF |
| 5 | Vac LCL Damped Resistance R_{LCLa} | 20 ohm |
| 6 | DC Link Capacitance C_{dc} | 10000 uF |
| 7 | Vbc Coupling Inductance 1 L_{b1} | 4 mH |
| 8 | Vbc Coupling Inductance 2 L_{b2} | 4 mH |
| 9 | Vbc LCL Capacitance C_{LCLb} | 5.63 uF |
| 10 | Vbc LCL Damped Resistance R_{LCLb} | 20 ohm |

The simulated system waveforms are shown in Figure14. Comparing them with the results obtained using RPC in Figure13. It can be observed that the compensation performance of HPQC in cophase traction power is more or less the same. For further investigations of the system performance, the simulated system statistics of cophase traction power without compensation, with RPC, and with HPQC are summarized in Table 3. It can be observed that with similar compensation performance, the minimum HPQC operation voltage is only 66% of that in RPC.

Table 3. Summarized System Statics 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 | | |

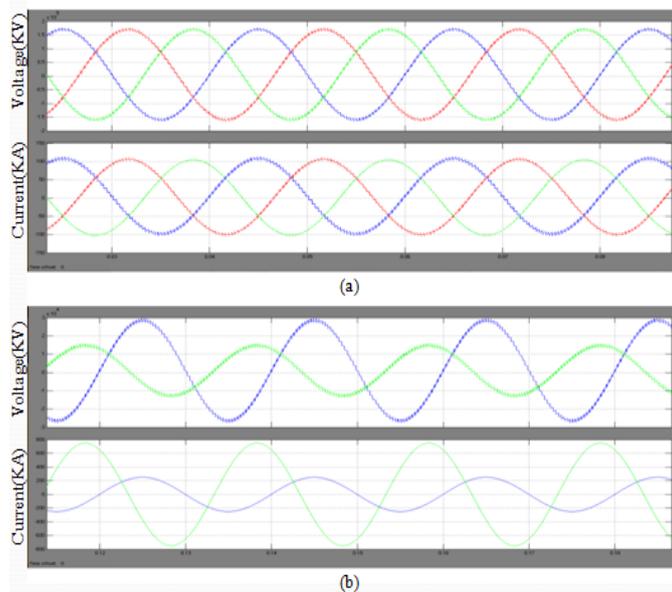


Figure 14. System Performances of the Proposed Cophase Traction Power Supply System with HPQC ($V_{dc}=27$ kV). (a) Three-Phase Power Source Voltage and Current Waveforms. (b) V_{ac} and V_{bc} Phase Voltage and Current Waveforms

6. CONCLUSION

A LLC-HPQC with reduced dc voltage operation compared to existing System during compensation is proposed in this project. The parameter design procedure 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 gives fast response the accuracy may be slightly lesser. In future we can replace fuzzy logic controller with Field Programmable Gate Array logic to improve the accuracy as well as steady state response of the system

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