

A New Railway Power Flow Control System Coupled With Asymmetric Double *LC* Branches

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Abstract—Facing the challenges of power quality problems and excessive neutral sections of conventional two-phase electric railway supply system, the way of adopting railway static power conditioner (RPC)-based single-phase supply system is a feasible solution. To enhance the cost-efficiency and reliability of RPC, a novel compensating system named asymmetric double *LC*-coupled railway power flow conditioner (ALC-RPFC) is proposed in this paper. The study indicates that compared with the conventional RPC, the proposed ALC-RPFC has an effective heavy-load compensating ability with lower power rating, which is benefit to enhance converter's operating efficiency and reliability. Besides, a design method for *LC* coupling branches mentioned in this paper is suitable for fluctuated railway loads, and is useful for designers of industrial applications as well. Finally, the good heavy-load compensating performance and power capacity decreasing ability of the ALC-RPFC are validated based on simulation and experiment results.

Index Terms—Asymmetric *LC*-coupling branches, electrical railway power system, parameter design, power capacity analysis, power flow control.

I. INTRODUCTION

WITH the wide application of high-speed and heavy-load trains in railway networks, the negative sequence current (NSC), reactive power, and harmonics injected into the power grids increase significantly, which seriously affects the stability of utility, and arouses widespread attention of related industrial departments and engineers [1]–[3].

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Considering the efficiency, adoption of the phase rotation technique is the most conventional method for electrical railway power system [4]. However, it lacks flexibility and cannot solve all power quality problems. Moreover, these problems will become more prominent in the remote areas with unrobust power system (e.g., mountainous and plateaus areas).

Compared to conventional transformers, the balance traction transformer (BTT) can have a better ability of suppressing NSC. Unfortunately, the ability of BTT to suppress NSC is affected by load variation. That is to say, the greater imbalance of two-phase loads, the worse ability of NSC suppression [5], [6]. Therefore, the three-phase power system can hardly be balanced by this method. Besides, this class of special-type transformer usually contains a complex winding structure, and it is also not beneficial for the elimination of harmonics and reactive power.

SCR-controlled static VAR compensator can also be used to compensate NSC and reactive power in traction supply systems. But it is difficult to get a satisfactory state in both technical and economic aspects [7].

To overcome the disadvantages, various IGBT- or IGCT-based active compensating systems were put forward in the last 20 years [8]–[21]. Among them, RPC gets more attention due to its universality [17]–[21]. It can deal with almost all power quality problems of two-phase and single-phase traction supply system. However, a relatively high compensation capacity and initial investment slow down its large-scale industrial application. Additionally, a high operating voltage (or dc-link voltage) of the converters is necessary. RPC has been used in a few traction substations (TSSs) of China and Japan since it was first proposed in 1993 [18]–[20].

Currently, the research on low-rated power conditioners is focused on hybrid active filters [22]–[25] and unified power quality conditioners [26]–[27]. Unfortunately, there is still few research related to the field of hybrid power conditioner for electrical railway power system. Two main reasons make it difficult to design the coupling passive elements of these conditioners: 1) the railway loads usually change rapidly within few seconds in real traction supply system (see Fig. 15 in Section VI), the complex working condition of locomotives make it difficult to estimate; 2) the power quality controllers should have the ability of comprehensive compensating NSC, reactive power, and harmonics in the same time with relatively low power rating. To the authors' knowledge, [9] proposed a useful configuration; [12], [14], and [15] discussed just one side of the three basic requirements stated previously, while some other researches are still analyzed, designed, and verified based on a static working

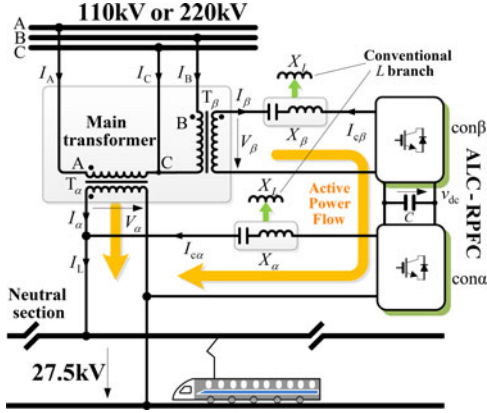


Fig. 1. Topology of ALC-RPFC system.

situation, which their industrial application value is limited and suspected significantly in real electrical railway power systems [21].

To overcome these problems, a new topology, ALC-RPFC, and the corresponding design method of the passive elements under load fluctuated working condition are proposed in this paper. As shown in Fig. 1, ALC-RPFC is mainly composed of two simple single-phase transformers and a back-to-back converter. Because the coupling parts between feeders and converters are two different LC-branches, we named it as asymmetric double LC-coupled railway power flow conditioner (i.e., ALC-RPFC); whereas the conventional RPC consists of two symmetric L-branches. The main purpose of this paper is to propose a systematic design method of the LC branches and the corresponding power capacity quantitative analysis method, which is suitable for the fluctuated electrical railway loads.

In the following, the topology of ALC-RPFC will be discussed in Section II. In Section III, the converter's operating performance is analyzed. The main contribution of this paper on the load variation based design method of LC-branches and the power capacity analysis will be given in Sections IV and V, respectively. Section VI gives the results of simulation and experiment. Finally, the conclusion is given in Section VII.

II. TOPOLOGY OF ALC-RPFC SYSTEM

Fig. 1 shows the topology of ALC-RPFC system. The three phase 110 kV (or 220 kV) high voltage grid is stepped down into 27.5-kV single-phase traction network by T_{α} so as to feed locomotives. While T_{β} 's secondary voltage, V_{β} , is not always 27.5 kV, its design value depends on the load's statistical results (see Section IV). Two power converters, con_{α} and con_{β} , back to back connection; through two LC branches, X_{α} and X_{β} , they are coupled with the main transformer, respectively.

Besides, multilevel topology can also be used in this conditioner, which can eliminate the need of two auxiliary bulky low frequency step-down transformers [9] (Note that the dc bus in this topology may not be unique [28]).

Fig. 2 shows the equivalent circuit of phase- α and β . Among which, V_{ck} and I_{ck} are the fundamental voltage and current

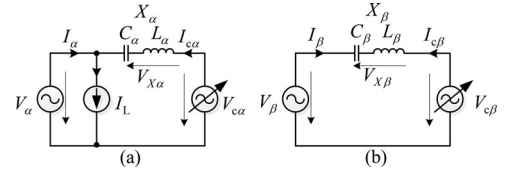
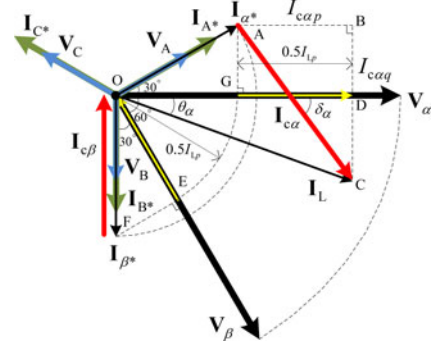

 Fig. 2. Equivalent circuits of phase- α and β . (a) Phase- α . (b) Phase- β .


Fig. 3. Compensating phasor diagram of ALC-RPFC system.

of converter k , respectively; X_k is the equivalent fundamental reactance and V_{Xk} the voltage drop of coupling branch in phase k , respectively; V_k and I_k are the secondary voltage and current of T_k ; I_L is the load's current ($k \in \{\alpha, \beta\}$).

III. OPERATING PROPERTY OF ALC-RPFC

A. Basic Requirements of Converters

Ignoring the influences of harmonics and turn's ratio difference between T_{α} with T_{β} ; the phasor diagram of ALC-RPFC is shown in Fig. 3 (Note that the voltages and currents of phase- β shown in Fig. 3 are converted to the same level of phase- α). ALC-RPFC should satisfy the following requirements [17]:

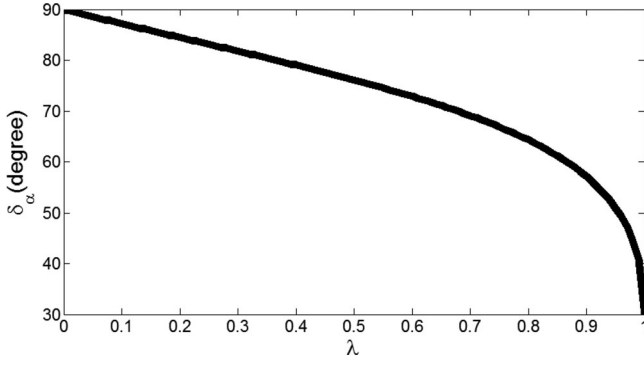
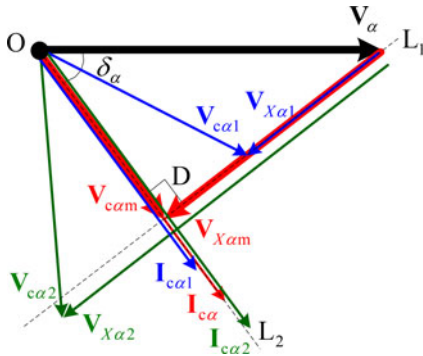
- 1) Transforming half of the load's active power from phase- β (EO, i.e., $0.5I_{Lp}$) to phase- α (GD, i.e., $0.5I_{Lp}$).
- 2) Compensating appropriate leading reactive power for phase- α (BC) and lagging reactive power for phase- β (EF).

Therefore, it can be observed from Fig. 3 that the output currents of T_{α} and T_{β} are converted from I_L and $\mathbf{0}$ into $I_{\alpha*}$ and $I_{\beta*}$, respectively. The primary three phase currents I_{A*} , I_{B*} , and I_{C*} induced by $I_{\alpha*}$ and $I_{\beta*}$ are balanced as well. Obviously, their PF is 1. Hence, the compensation currents of con_{α} and con_{β} are $I_{c\alpha}$ and $I_{c\beta}$, respectively. By the way, this compensating principle is also useful for RPC [17].

To get the requirements stated previously, referring to Fig. 3, δ_{α} ($\delta_{\alpha} = \angle V_{\alpha} - \angle I_{c\alpha}$) and the load's PF, λ ($\lambda = \cos\theta_{\alpha}$), should satisfy

$$\delta_{\alpha} = \arctan \left(\frac{|I_{c\alpha q}|}{|I_{c\alpha p}|} \right) = \arctan \left(\frac{1}{\sqrt{3}} + 2\sqrt{\frac{1}{\lambda^2} - 1} \right) \quad (1)$$

where $I_{c\alpha p}$ and $I_{c\alpha q}$ are the active and reactive part of $I_{c\alpha}$, respectively (i.e., AB and BC in Fig. 3). From (1), the relationship

Fig. 4. Curves of $\delta_\alpha(\lambda)$.Fig. 5. Phasor diagram of $\text{con}\alpha$ when δ_α is constant.

of δ_α and λ can be obtained as shown in Fig. 4. Obviously, δ_α is in inverse proportion to λ .

Besides, the compensating current $I_{c\alpha}$ of $\text{con}\alpha$ and load current I_L should satisfy (2), i.e.

$$I_{c\alpha} = \sqrt{I_{c\alpha p}^2 + I_{c\alpha q}^2} = \varepsilon I_L \quad (2)$$

where

$$\varepsilon = \sqrt{-\frac{2}{3}\lambda^2 + \frac{\lambda}{\sqrt{3}}\sqrt{1-\lambda^2} + 1}. \quad (3)$$

B. Output Voltage of $\text{Con}\alpha$

From Fig. 2(a), $\text{con}\alpha$'s fundamental output voltage, $V_{c\alpha}$, can be expressed as

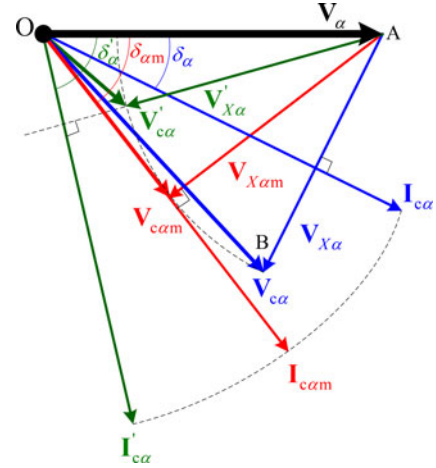
$$V_{c\alpha} = V_\alpha + jX_\alpha I_{c\alpha} = f(V_\alpha, X_\alpha, I_{c\alpha}, \delta_\alpha) \quad (4)$$

where $X_\alpha = \omega L_\alpha - 1/\omega C_\alpha$ is the LC branch's fundamental reactance of phase- α ; δ_α is the phase difference between V_α and $I_{c\alpha}$; $f(\ast)$ represents a function of V_α , X_α , $I_{c\alpha}$, and δ_α .

For an electric railway supply system, the normal voltage of V_α is a constant, while X_α will be discussed in the next section. So the main task of this part is to discuss the basic relationship among $V_{c\alpha}$, $I_{c\alpha}$, and δ_α .

1) *Situation 1*: The phase of $I_{c\alpha}$ is constant (i.e., δ_α unchanging), but its amplitude variable.

Fig. 5 shows the phasor diagram of $\text{con}\alpha$'s output voltage ($X_\alpha < 0$) when δ_α is constant. It can be seen from Fig. 5 that the

Fig. 6. Phasor diagram of $\text{con}\alpha$ when $I_{c\alpha}$ is constant.

terminal point of $V_{c\alpha}$ shifts in the vertical line of $I_{c\alpha}$ ($V_{c\alpha 1} \rightarrow V_{c\alpha m} \rightarrow V_{c\alpha 2}$) when $I_{c\alpha}$ varies along with L_2 ($I_{c\alpha 1} \rightarrow I_{c\alpha} \rightarrow I_{c\alpha 2}$). The minimum value of $V_{c\alpha}$, $V_{c\alpha m}$, precisely appears in the intersection point of L_1 and L_2 (i.e., point D). So, for every fixed value of δ_α , there is a corresponding $V_{c\alpha m}$, and it satisfies the following equations:

$$\begin{cases} V_{c\alpha m} = V_\alpha \cos \delta_\alpha \\ |X_{\alpha m}| = \frac{1}{\omega C_\alpha} - \omega L_\alpha = \frac{V_\alpha \sin \delta_\alpha}{I_{c\alpha}} \end{cases} \quad (5)$$

where $X_{\alpha m}$ is the LC branch's fundamental reactance of phase- α when $V_{c\alpha} = V_{c\alpha m}$.

Because $\delta_\alpha \in [30^\circ, 90^\circ]$ (see Fig. 4), it can be calculated from (5) that $V_{c\alpha m} \in [0, 0.866V_\alpha]$. That is to say, no matter the changes of $I_{c\alpha}$'s phasor angle, $V_{c\alpha m}$ is always less than V_α , and its maximum value is only $0.866V_\alpha$.

2) *Situation 2*: The amplitude of $I_{c\alpha}$ is constant, but its phase variable (i.e., δ_α variable).

Fig. 6 shows the phasor diagram of $\text{con}\alpha$ when $I_{c\alpha}$ is a constant ($X_\alpha = X_{\alpha m} < 0$). The variables shown in Fig. 6 satisfy the following relationship:

$$\begin{cases} I_{c\alpha}' = I_{c\alpha m} = I_{c\alpha} \\ V_{X\alpha}' = V_{X\alpha m} = V_{X\alpha} \\ \delta_\alpha' > \delta_{\alpha m} > \delta_\alpha \\ V_{c\alpha}' > V_{c\alpha m} > V_{c\alpha} \end{cases} \quad (6)$$

It can be seen from Fig. 6 that the smaller the phase angle between V_α with the compensating current (i.e., $\delta_\alpha < \delta_{\alpha m} < \delta_\alpha'$), the larger the output voltage of $\text{con}\alpha$ (i.e., $V_{c\alpha} > V_{c\alpha m} > V_{c\alpha}'$). Because δ_α is inversely proportional to λ (see Fig. 4), it can be concluded from Fig. 6 that when both $I_{c\alpha}$ and X_α are constant, larger λ (or smaller δ_α) corresponds to larger $V_{c\alpha}$. Then, the apparent power of $\text{con}\alpha$ meets the relationship of $V_{c\alpha}' I_{c\alpha}' < V_{c\alpha m} I_{c\alpha m} < V_{c\alpha} I_{c\alpha}$.

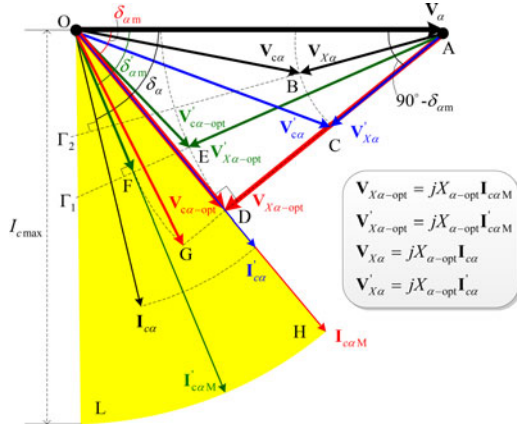


Fig. 7. Phasor diagram of ALC-RPFC in the variable load condition.

IV. PARAMETER DESIGN AND SYSTEM CONTROL BASED ON THE FLUCTUATED LOAD CONDITION

A. Parameter Design of Phase- α

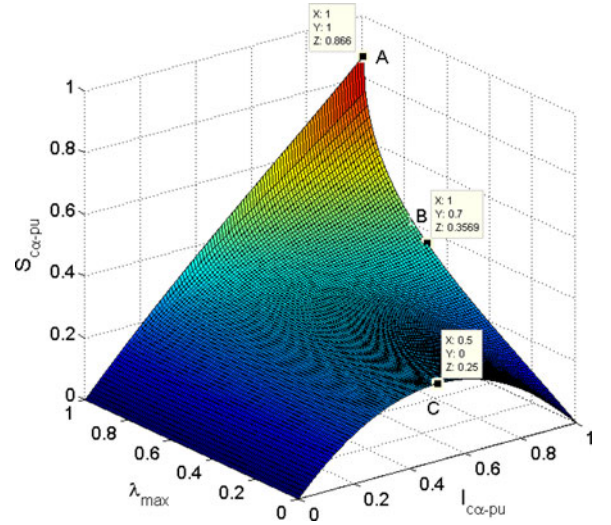
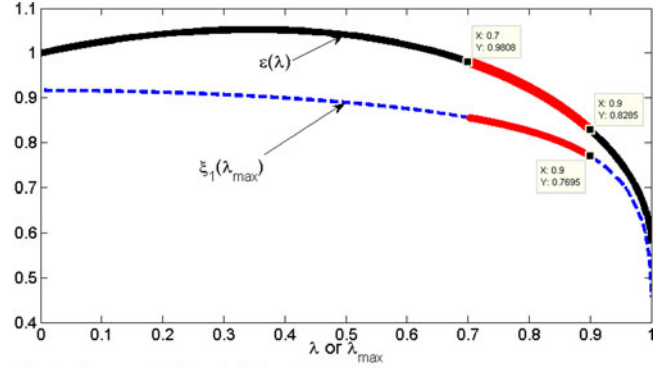
1) *Synergetic Design Principle Between X_α With $\text{con}\alpha$* : It can be deduced from the previous discussions that X_α is a key parameter of ALC-RPFC, which has significant influence for the output performance of the power conditioner. To give an optimal balance between compensating performance and cost-efficiency, we will give a synergetic design guideline for X_α and $\text{con}\alpha$:

- 1) When the traction supply system operates in the heavy-load situation, the output voltage of $\text{con}\alpha$ should be as low as possible. It allows ALC-RPFC to get the satisfactory heavy-load compensating ability with lower voltage rating and switching frequency. And it also results in higher system reliability and operating efficiency, because the supply system's power quality over-standard and converter faults always occur in the heavy-load situation [14], [31]–[32].
- 2) In the premise of satisfying the first designing principle, an appropriate X_α should also make the apparent power of the converter as high as possible. In this way, the power capacity utilization rate of the compensating system can be increased.
- 3) In the typical variation range of load currents, the designed X_α should make the compensating system to have the obvious economic advantage than conventional RPC.

2) *Designing Idea of X_α* :

a) *Realization of the first design principle*: In order to meet the first designing principle, the second term of (5) seems to be an available method. Unfortunately, the load working condition in the real traction network is much complex, so that it is difficult to estimate. It means the parameter design method in static working condition shown in (5) can not be used for real applications. To solve the problem, this part will give a useful one. Its designing idea and practical calculation method will be given in the following statements.

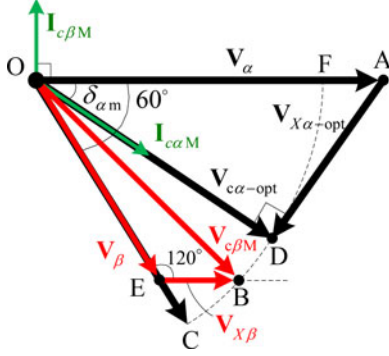
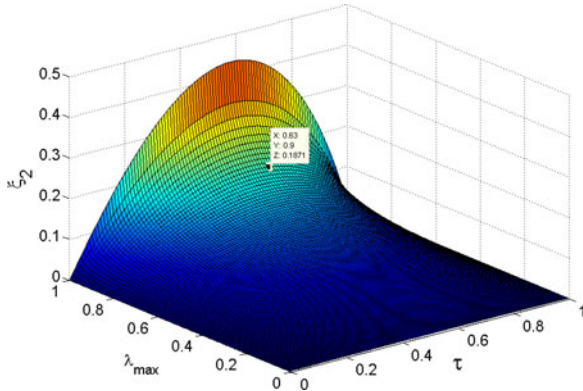
Fig. 7 shows the phasor diagram of ALC-RPFC at four typical working conditions, in which, I_{ca} , I_{ca}' , I_{camax} , and I_{camax}' are the corresponded four compensating currents of $\text{con}\alpha$, and


 Fig. 8. Relationship among $S_{c\alpha}$, $I_{c\alpha}$, and λ_{\max} (Note that the base values are selected as $V_B = V_\alpha$, $I_B = I_{c\alpha M}$.)

 Fig. 9. Curves of $\varepsilon(\lambda)$ and $\xi_1(\lambda_{\max})$.

satisfying $I_{ca} = I_{ca}' < I_{camax} = I_{camax}'$. The phase differences between V_α with that four currents are δ_α , $\delta_{\alpha m}$, $\delta_{\alpha m}$, and $\delta_{\alpha m}'$, respectively. Obviously, $\delta_{\alpha m}$ is the minimum one of them. Considering $\delta_\alpha \in [30^\circ, 90^\circ]$ (see Fig. 4), it can be deduced from Fig. 7 that $30^\circ \leq \delta_{\alpha m} \leq \delta_\alpha \leq 90^\circ$. For discussing convenience, we define $I_{camax} = I_{camax}' = I_{cmax}$ (see Fig. 7) as the maximal rms-value of the compensating currents; and $\delta_{\alpha m}$ as the minimal angle difference between V_α with $\text{con}\alpha$'s compensating currents.

Besides, it can also be observed from Fig. 7 that, ΔABO , ΔACO , ΔADO , and ΔAEO are the voltage phasor triangles of $\text{con}\alpha$ corresponding to I_{ca} , I_{ca}' , I_{camax} , and I_{camax}' , respectively. The voltage drops of the LC branch in these four cases are $V_{X\alpha}$, $V_{X\alpha}'$, $V_{X\alpha-opt}$, and $V_{X\alpha-opt}'$, and their expressions are shown in the lower right corner of Fig. 7 ($X_{\alpha-opt}$ is the optimal reactance of X_α , and it will be discussed in the following text).

So, from Fig. 7, it can be concluded that, no matter how the railway load changes, all the compensating currents are located in the yellow fan-shaped area of OHL. Therefore, I_{ca} and I_{ca}' are the representative compensating currents of $\text{con}\alpha$

Fig. 10. Phasor diagram of phase- β .Fig. 11. Design surface of ξ_2 .

when their amplitudes is less than $I_{cm\max}$. While $I_{c\alpha m}$ and $I_{c\alpha m}'$ are the representative ones when $\text{con}\alpha$'s compensating currents is equal to $I_{cm\max}$. Besides, we must emphasize here that the load's PF is not a fixed value in both of those two cases; it changes the value along with δ_{α} .

To ensure the safety of the converters, it is reasonable to select the maximal compensating current as the normal current of $\text{con}\alpha$, e.g., $I_{c\alpha m} = I_{c\alpha m}' = I_{cm\max}$ should be selected as the normal current. Additionally, when the compensating current equals $I_{cm\max}$, a suitable X_{α} should make $\text{con}\alpha$ operate at the minimal output voltage, e.g., OD and OF shown in Fig. 7. Because selecting the minimal output voltage as the normal voltage, a minimal apparent power can be obtained. From Fig. 7, it can be observed that ΔADO and ΔAFO satisfy the condition stated previously, which can be used as the voltage triangle to design X_{α} (Note that ΔAFO is the representative design triangle when the phase of the normal compensating current large than $\delta_{\alpha m}$).

In the following, we will select an optimal one in those two representative cases: 1) If ΔADO is adopted to design X_{α} , it can be seen from Fig. 7 that when the compensating current changes from the normal current $I_{c\alpha m}$ to another normal one $I_{c\alpha m}'$, the output voltage of $\text{con}\alpha$ will transform from OD to OE. Obviously $\text{OE} < \text{OD}$, which means, when the compensating current shifts along with arc HL, adopting ΔADO to design X_{α} , $\text{con}\alpha$'s output voltage will not exceed OD. 2) If ΔAFO is adopted to

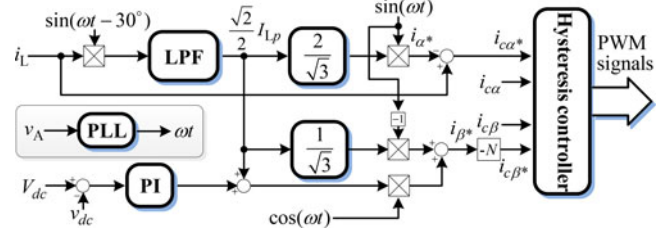


Fig. 12. Control diagram of low-rated ALC-RPFC.

design X_{α} , similarly, when the compensating current changes from the normal current $I_{c\alpha m}$ to another normal current $I_{c\alpha m}'$, the output voltage of $\text{con}\alpha$ will transform from OF to OG. Because $\text{OG} > \text{OD}$, so $\text{con}\alpha$'s apparent power in this situation is larger than that of the ΔADO -based design method, which has negative influence on converter's initial cost and reliability.

Hence, to get the minimal output voltage and apparent power of $\text{con}\alpha$ in the condition of load changes (i.e., the first design principle), select ΔADO to design X_{α} is better than others. From ΔADO , the optimal $|X_{\alpha}|$, $|X_{\alpha\text{-opt}}|$, can be calculated by

$$|X_{\alpha\text{-opt}}| = \frac{\text{AD}}{I_{c\alpha M}} = \frac{V_{X\alpha\text{-opt}}}{I_{c\alpha M}} = \frac{V_{\alpha} \sin \delta_{\alpha m}}{I_{c\alpha M}} \quad (7)$$

where $I_{c\alpha m}$ is the maximum value of $I_{c\alpha}$; $\delta_{\alpha m}$ is the minimum compensating current angle of $\text{con}\alpha$, and it satisfies [see (1)]

$$\delta_{\alpha m} = \arctan \left(\frac{1}{\sqrt{3}} + 2\sqrt{\frac{1}{\lambda_{\max}^2} - 1} \right) \quad (8)$$

where λ_{\max} is the maximum PF of load current.

b) Verification of the second design principle: Referring to Fig. 7, when $I_{c\alpha m}$ (normal current) decreases to $I_{c\alpha}'$, ΔADO degenerates into ΔACO , and the output voltage of $\text{con}\alpha$, however, increases from $V_{c\alpha\text{-opt}}$ (i.e., OD) to $V_{c\alpha}'$ (i.e., OC). So, the calculating expression of X_{α} , (7), deduced from ΔADO may not be able to ensure that $\text{con}\alpha$ has the maximum apparent power in the condition of load changes. Moreover, all those variables are strongly related to load's PF. So, whether (7) meets the secondary designing principle of X_{α} has to be verified.

Based on the conclusion deduced from Figs. 6, from 7 it can be concluded that the apparent power of $\text{con}\alpha$ calculated by ΔADO and ΔACO is larger than that of ΔAEO and ΔABO , respectively. That is to say, the terminal point of $V_{c\alpha}$ (point B) in ΔABO (the most ordinary working condition of $\text{con}\alpha$) has to be constrained shifting in line AD, can the maximum value of $S_{c\alpha}$ (the apparent power of $\text{con}\alpha$) may be obtained. In this case, $I_{c\alpha} \rightarrow I_{c\alpha}'$, $\Delta\text{ABO} \rightarrow \Delta\text{ACO}$.

From ΔACO , $S_{c\alpha}$ can be calculated by

$$\begin{aligned} S_{c\alpha} &= I_{c\alpha} V'_{c\alpha} \\ &= I_{c\alpha} \sqrt{V_{\alpha}^2 + I_{c\alpha}^2 X_{\alpha\text{-opt}}^2 - 2I_{c\alpha} |X_{\alpha\text{-opt}}| V_{\alpha} \sin \delta_{\alpha m}}. \end{aligned} \quad (9)$$

Note that because $\Delta\text{ABO} \cong \Delta\text{ACO}$, $I_{c\alpha}'$ is substituted by $I_{c\alpha}$ in (9). Fig. 8 shows the relationship among $S_{c\alpha}$, $I_{c\alpha}$, and λ_{\max} , which is obtained by the per-unit expression of (9).

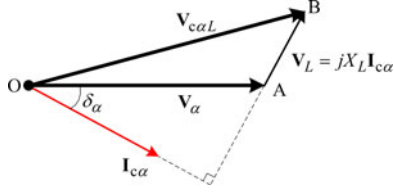


Fig. 13. Phasor diagram of RPC.

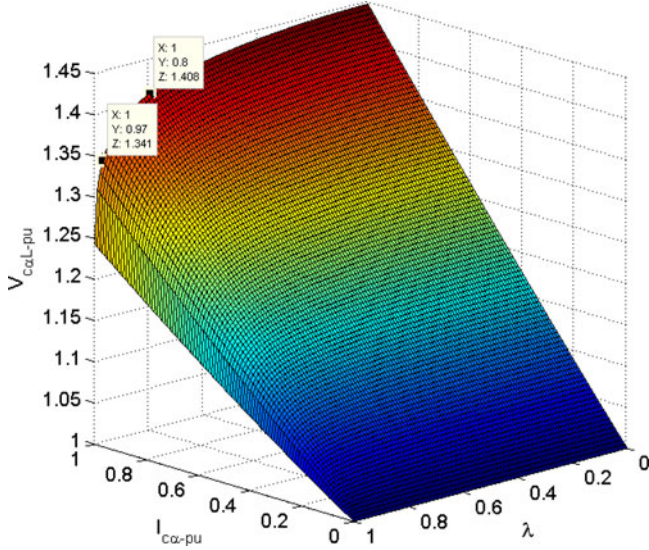

 Fig. 14. 3-D plot of $V_{c\alpha L-pu}$ (Note that the base values are $V_B = V_\alpha$, $I_B = I_{c\alpha M}$.)

 TABLE I
 SPECIFICATIONS OF THE TSS

Item	Values
Grid voltage/short-circuit capacity (S_d)	110 kV \pm 5%/530 MVA
Type of traction transformer/capacity	V/v transformer/20.5 MVA (phase- α :12.5 MVA, Phase- β :8 MVA)
V/v transformer's short-circuit impedance	10.25% (phase- α) 10.67% (phase- β)
Feeder's normal voltage	27.5 kV

It can be observed from Fig. 8 that, when $\lambda_{max} \in [0.7, 1]$ (the typical PF of locomotives), the maximum value of $S_{c\alpha}$ appears exactly when $I_{c\alpha} = 1.0$ p.u. (AB segment). That is to say, for electrical railway loads, the LC branch's design method shown in (7) can successfully make $S_{c\alpha}$ reach its maximum value when $I_{c\alpha} = I_{c\alpha M}$ [i.e., $\delta_\alpha = \delta_{\alpha M}$ (or $\lambda = \lambda_{max}$) and $I_{c\alpha} = I_{c\alpha M}$]. And it also equals the normal apparent power of $con\alpha$. Therefore, (7) is compatible with the secondary designing principle of X_α .

The third designing principle of X_α will be discussed in Section V. By the way, because when $I_{c\alpha} = I_{c\alpha M}$, $con\alpha$'s output voltage gets its optimal value ($V_{c\alpha-opt}$), so we named this method as the optimal voltage design method (OVD) of X_α .

3) *Calculating Method of $X_{\alpha-opt}$ for Practical Application:* Because $I_{c\alpha}$ cannot be measured directly, (7) is not a convenient calculating method for practical application. The following, we will give a useful one for designing $X_{\alpha-opt}$.

The curve of $\varepsilon(\lambda)$ is shown in Fig. 9 [originate from (3)]. Usually, the probability of locomotives' PF locates in 0.7~0.9 is much higher than other values. While, it can be observed from Fig. 9 that when $\lambda \in [0.7, 0.9]$, $\varepsilon(\lambda)$ locates in a narrow interval of 0.8285~0.9808, which means $I_{c\alpha}$ is approximately proportional with I_L . So, referring to (2), $I_{c\alpha M}$ can be approximately expressed as

$$I_{c\alpha M} \approx \frac{I_{LM}}{0.2} \int_{0.7}^{0.9} \varepsilon(\lambda) d\lambda = \varepsilon_{aver} I_{LM} = 0.916 I_{LM} \quad (10)$$

where I_{LM} is the maximum value of I_L , ε_{aver} is the average value of ε when $\lambda \in [0.7, 0.9]$.

Remark 1: For different electrical railway power system, the load's PF may not accurately distributes in 0.7~0.9, so it is better to modify ε_{aver} 's value flexibly based on the form shown in (10), by applying the real statistic result of λ in practical applications.

Substituting (10) and (8) into (7), the final practical used expression of $|X_{\alpha-opt}|$ can be expressed as

$$|X_{\alpha-opt}| = \frac{1}{\omega C_\alpha} - \omega L_\alpha = \xi_1 \frac{V_\alpha}{I_{LM}} \quad (11)$$

where

$$\xi_1 = \varepsilon_{aver} \frac{\lambda_{max}/2\sqrt{3} + \sqrt{1 - \lambda_{max}^2}}{\sqrt{-\frac{2}{3}\lambda_{max}^2 + \frac{\lambda_{max}}{\sqrt{3}}\sqrt{1 - \lambda_{max}^2} + 1}} \quad (12)$$

For the consideration of designing convenience, the curve of $\xi_1(\lambda_{max})$ is also given in Fig. 9 (dotted line).

The concept of 95%-probability value is always be used in practical cases, so (11) can be also rewritten as

$$|X_{\alpha-opt}| = \frac{1}{\omega C_\alpha} - \omega L_\alpha = \xi_1 |_{\lambda_{max}=\lambda_{95\%(U)}} \frac{V_\alpha}{I_{L-95\%(U)}} \quad (13)$$

where $\lambda_{95\%(U)}$ and $I_{L-95\%(U)}$ are the upper-95%-probability value of λ and I_L , respectively.

Therefore, in the premise of satisfying (12) or (13), L_α and C_α can be configured flexibly according to practical situation (sometimes they are tuned at n th harmonics).

B. Parameter Design of Phase- β

Fig. 10 shows the phasor diagram of phase- β , in which, ΔADO is the voltage triangle of $con\alpha$, and it is the same with ΔADO shown in Fig. 7. $I_{c\beta M}$ is the maximum compensating current phasor of $con\beta$, and it leads V_α 90°. $V_{c\beta M}$ is the maximum output voltage of $con\beta$. V_β lags V_α 60°.

In order to reduce the cost, improve the reliability of converters and design flexibility of the coupling branch, it is reasonable to make X_β meet the following design principles:

- 1) It is better to make $V_{c\beta M} = V_{c\alpha-opt}$ when the compensating current of $con\alpha$ reaches its maximum value $I_{c\alpha M}$. This is because it can ensure the operating symmetry of

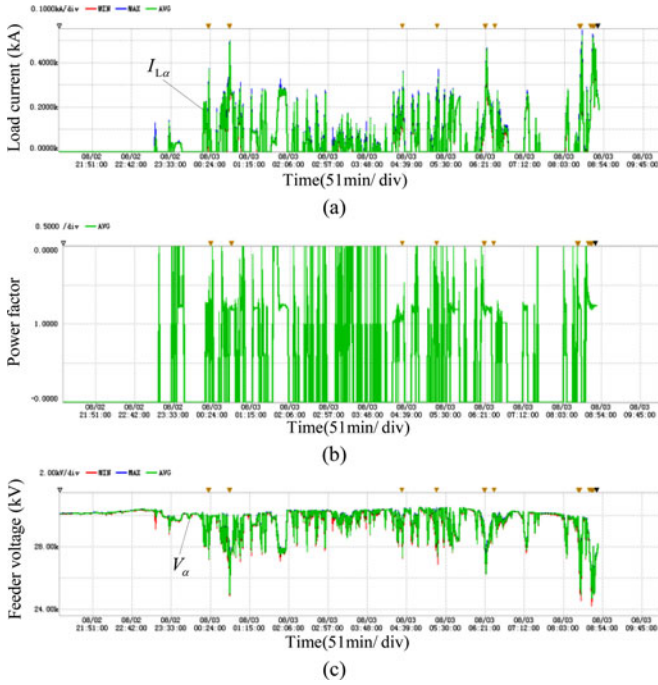


Fig. 15. Phase- α 's time-plot waveforms of a real TSS. (a) Load current ($I_{L\alpha}$). (b) Load's PF. (c) Feeder voltage (V_α).

$\text{con}\alpha$ and $\text{con}\beta$, when the whole compensation system works in the severest working condition.

- 2) In the premise of avoiding large inductance, designers should have sufficient flexibility to match the parameters of coupling branch when V_β is a fixed value (it often happens in the renovation projects). It is convenient for device selection and also helps to reduce the costs and designing difficulties.

To meet the aforementioned designing principles, adopting $L_\beta - C_\beta$ coupling branch is an ideal scheme (Note that C_β dominates the branch in fundamental frequency.). Then, the typical voltage triangle of $\text{con}\beta$ in Fig. 10 is ΔBEO , where

$$\begin{cases} V_\beta = \text{OE} = \tau V_{c\alpha-\text{opt}}, 0 < \tau < 1 \\ V_{X\beta} = \text{EB} = |X_\beta| I_{c\beta M} \\ V_{c\beta M} = \text{OB} = \text{OD} = V_{c\alpha-\text{opt}} \end{cases} \quad (14)$$

in which EB is the voltage drop of the LC-coupling branch, X_β is the fundamental reactance of the LC branch of phase- β .

Besides, V_β should be designed less than $V_{c\alpha-\text{opt}}$ (i.e., $V_\beta = \tau V_{c\alpha-\text{opt}}, 0 < \tau < 1$). Referring ΔADO in Fig. 10, and combine (14) and (7)–(12), it can be calculated that

$$\begin{aligned} V_\beta &= \tau \sqrt{V_\alpha^2 - V_{X\alpha-\text{opt}}^2} \\ &= \frac{\tau \lambda_{\max}}{2 \sqrt{-\frac{2}{3} \lambda_{\max}^2 + \frac{\lambda_{\max}}{\sqrt{3}} \sqrt{1 - \lambda_{\max}^2} + 1}} V_\alpha. \end{aligned} \quad (15)$$

Considering that when $I_{c\beta} = I_{c\beta M}$, the active part of I_L , I_{Lp} ($I_{Lp} = \lambda I_L$), bound to reach its maximum value, so $I_{c\beta M}$ can be easily calculated by the current relationship shown in

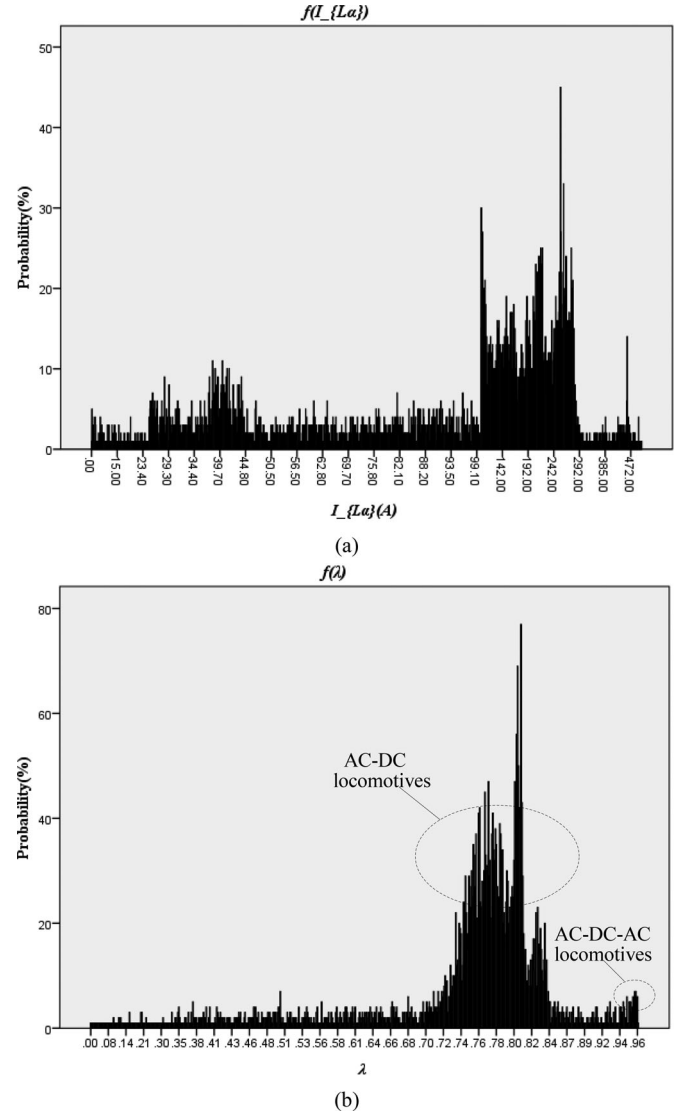


Fig. 16. Probability density curves of $I_{L\alpha}$ and PF. (a) Probability density curves of $I_{L\alpha}$ [i.e., $f(I_{L\alpha})$]. (b) Probability density curves of PF [i.e., $f(\lambda)$].

Fig. 3, i.e.

$$I_{c\beta M} = \frac{N I_{LM} \lambda_{\max}}{2 \cos 30^\circ} = N \frac{I_{LM} \lambda_{\max}}{\sqrt{3}} \quad (16)$$

where $N = V_\alpha / V_\beta$.

By using the cosine theorem in ΔBEO (see Fig. 10) and combining (14)–(16), $|X_\beta|$ can be calculated by

$$|X_\beta| = \frac{1}{\omega C_\beta} - \omega L_\beta = \xi_2 \frac{V_\alpha}{I_{LM}} \quad (17)$$

where

$$\xi_2 = \frac{\sqrt{3} \tau (\sqrt{4 - 3\tau^2} - \tau) \cos^2 \delta_{\alpha m}}{2 \lambda_{\max}}, 0 < \tau < 1. \quad (18)$$

Similar to design X_α , instead of λ_{\max} and I_{LM} , $\lambda_{95\%}(U)$ and $I_{L-95\%}(U)$ can also be used in (15) and (17), (18) to calculate V_β and X_β in practical applications.

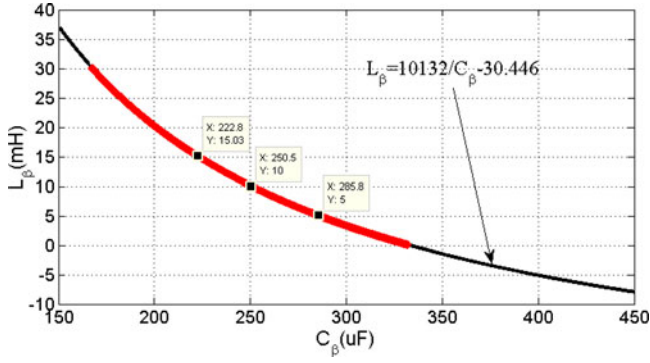

 Fig. 17. Designing curve of L_β and C_β .

 TABLE II
 SIMULATION PARAMETERS OF ALC-RPFC AND RPC*

V_β /kV	L_α /mH	C_α /μF	L_β /mH	C_β /μF	L /mH	C /mF
10	6.3	65	10	250	45	20

* L_α and C_α is resonated at fifth harmonics; C is the dc-link capacitance of converters; L is the coupling-inductance of RPC.

The design curve of L_β and C_β can be easily obtained from (17) and a real design example is shown in Fig. 17 of Section VI, which can be used to flexibly configure L_β and C_β according to the actual situation. For convenience of design, Fig. 11 gives the design surface of ξ_2 .

C. Control System of Low-Rated Laboratory Model

Fig. 12 shows the control diagram of a low-rated ALC-RPFC. Based on the Fourier transformation theory, it can be verified that the output signal of low passive filter is $I_{Lp}/\sqrt{2}$ (I_{Lp} is the active part of I_L) [17]. $i_{\alpha*}$ and $i_{\beta*}$ are the expected output currents of T_α and T_β , respectively. Their phasors are $I_{\alpha*}$ and $I_{\beta*}$ in Fig. 3. The signals $i_{c\alpha*}$ and $i_{c\beta*}$ are the references of the compensating currents, which are controlled by a hysteresis controller with the actual compensating currents $i_{c\alpha}$ and $i_{c\beta}$. While, the dc-link voltage is controlled by PI controller and regulated by $\text{con}\beta$. This control diagram is also useful for low-rated RPC.

For the consideration of resonance, when the control method shown in Fig. 12 is adopted, ALC-RPFC can be equivalent to an active filter with infinite harmonic damping factor in harmonic frequencies, so the harmonic resonance can be suppressed effectively [29], [30].

V. POWER CAPACITY ANALYSIS AND DC-LINK VOLTAGE DESIGN

For the same compensating task, ALC-RPFC and RPC have the same compensating currents, so the converters' power ratings of two systems are mainly decided by the output voltage of $\text{con}\alpha$ [26], [27]. More accurately to say, is the dc-link voltage.

A. Proposed ALC-RPFC

It can be observed from ΔACO in Fig. 7 that, when $I_{c\alpha'}$ increases to $I_{c\alpha m}$, $V_{X\alpha'} \rightarrow V_{X\alpha-\text{opt}}$, then $\text{con}\alpha$'s output volt-

 TABLE III
 SPECIFICATIONS OF LOAD CURRENTS

	RMS/A	1th/A	3th/A	λ	THD%
$i_{\alpha L1}$	206.4	203.0	32.4	0.805	18.19
$i_{\alpha L2}$	314.4	312.7	57.0	0.746	20.57
$i_{\alpha L1} + i_{\alpha L2}$	524.3	514.9	89.4	0.812	19.16

age, $V_{c\alpha'}$, trends to its minimum value $V_{c\alpha-\text{opt}}$. In addition, it can also be observed from ΔAEO of Fig. 7 that when $I_{c\alpha m} \rightarrow I_{c\alpha m'}$, $\delta_{\alpha m} \rightarrow \delta_{\alpha m'}$, which means the PF becomes smaller. Obviously, the output voltage of $\text{con}\alpha$, $V_{c\alpha-\text{opt}}$, is less than $V_{c\alpha-\text{opt}}$.

Therefore, it can be concluded that, for a fixed dc-link voltage, the heavier the load or the lower the PF of the locomotive, the better the compensating performance of ALC-RPFC when OVDM is adopted.

In fact, the power quality problems can be neglected when the traction network feeds for light-loaded locomotives with high PF. Because all those NSC or reactive power injected into the utility are attenuated by system's short-circuit capacity. As mentioned previously, since the converter of ALC-RPFC has lower operating voltage in heavy-loaded or low PF situation, so ALC-RPFC is exactly suitable for the heavy-loaded or low PF cases, which has the biggest influence on the utility. This means, the proposed system can meet the power quality requirement of the utility when the dc-link voltage is designed less than the peak value of feeder voltage, i.e., $\sqrt{2}V_\alpha$. Reference to "Appendix A," a satisfactory compensating performance can be obtained when the dc-link voltage of ALC-RPFC is designed within $1.1 \sim 1.35 V_\alpha$.

B. Conventional RPC

For RPC, the situation is reversed. It can be seen from Fig. 13 that, when $I_{c\alpha}$ increases, the converter's output voltage $V_{c\alpha L}$ of RPC (i.e., OB) will be much larger than V_α (i.e., OA). That is to say, the dc-link voltage of RPC has to be designed much higher than $\sqrt{2}V_\alpha$ when the traction supply system feeds for heavy-load trains. Hence, the voltage rating of power devices along with the initial investment have to be increased, but the system's reliability and operating efficiency decrease consequently.

From Fig. 13, $V_{c\alpha L}$ can be easily obtained from ΔABO , i.e.

$$V_{c\alpha L} = \sqrt{V_\alpha^2 + I_{c\alpha}^2 X_L^2 + 2I_{c\alpha} X_L V_\alpha \sin \delta_\alpha} \quad (19)$$

where X_L is the reactance of the coupling inductance of RPC.

Let $X_L = \xi |X_{\alpha-\text{opt}}|$, ($\xi > 0$), and considering (7), the per-unit form of (19) can be calculated by

$$V_{c\alpha L-\text{pu}} = \sqrt{(\xi I_{c\alpha-\text{pu}} \sin \delta_{\alpha m})^2 + 2\xi I_{c\alpha-\text{pu}} \sin \delta_{\alpha m} \sin \delta_\alpha + 1} \quad (20)$$

where the subscript "pu" represents the per-unit form of each variable. The base values are selected as $V_B = V_\alpha$, $I_B = I_{c\alpha m}$.

Based on the design experience, X_L is always designed into $18 \sim 25 \Omega$ when the power rating of RPC's converter reaches $4 \sim 15 \text{ MVA}$ [19], [20]. Then $\xi \in [0.45, 0.55]$ (Section VI shows

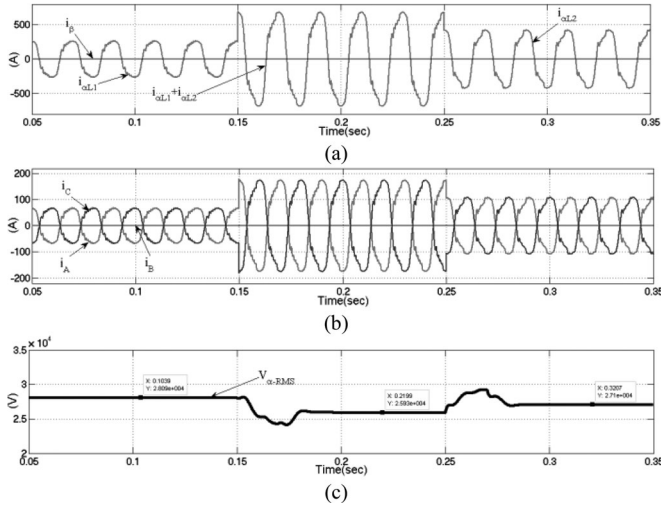


Fig. 18. Simulation waveforms without compensation. (a) Load currents. (b) Primary three phase currents. (c) Feeder voltage's RMS value of phase- α .

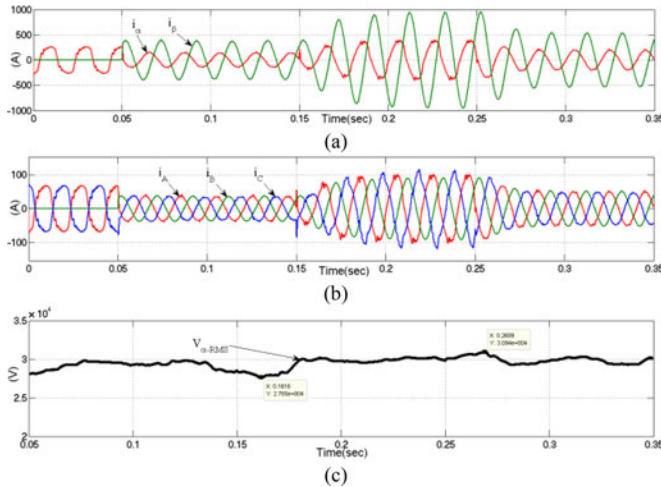


Fig. 19. Simulation waveforms of RPC system when $V_{dc-L} = 66.7$ kV. (a) Secondary output currents of main transformer. (b) Primary three phase currents. (c) Feeder voltage's RMS value of phase- α .

a practical designing example of X_α , in which $|X_{\alpha-opt}| = 46.9\Omega$. Let $\xi = 0.5$ and $\lambda_{max} = 0.9$ (i.e., $\delta_{\alpha m} = 57.1$, because the probability of PF's upper-95%-probability value of locomotives distributes within 0.85~0.93 is much higher than other values), the 3-D plot of $V_{\alpha L}$ can be obtained from (20), and is shown in Fig. 14.

It can be seen from Fig. 14 that when $\lambda = 0.8$ (the typical PF of ac-dc locomotives) and $I_{c\alpha} = 1.0$ p.u., $V_{\alpha L}$ reaches its maximum value $1.408V_\alpha$. So the dc-link voltage of RPC V_{dc-L} has to be designed to the peak value $\sqrt{2}V_{\alpha L}$ without consideration of harmonics compensation, i.e., $V_{dc-L} \approx 2V_\alpha$. Compared with the dc-link voltage $V_{dc-LC} = 1.1 \sim 1.35 V_\alpha$ of ALC-RPFC, the power rating of RPC increases 32.5%~45%. If the function of active filter is considered, the power rating save ratio of ALC-RPFC will be further increased. On the other hand, considering the locomotive with new generation ac-dc-ac driver

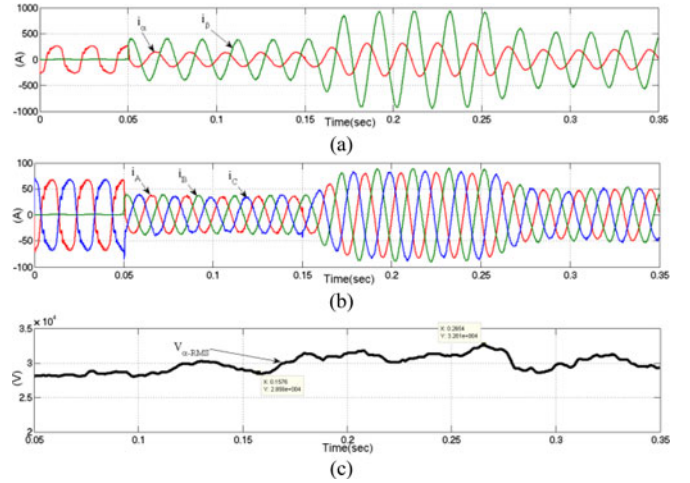


Fig. 20. Simulation waveforms of ALC-RPFC system when $V_{dc-LC} = 38.9$ kV. (a) Secondary output currents of main transformer. (b) Primary three phase currents. (c) Feeder voltage's RMS value of phase- α .

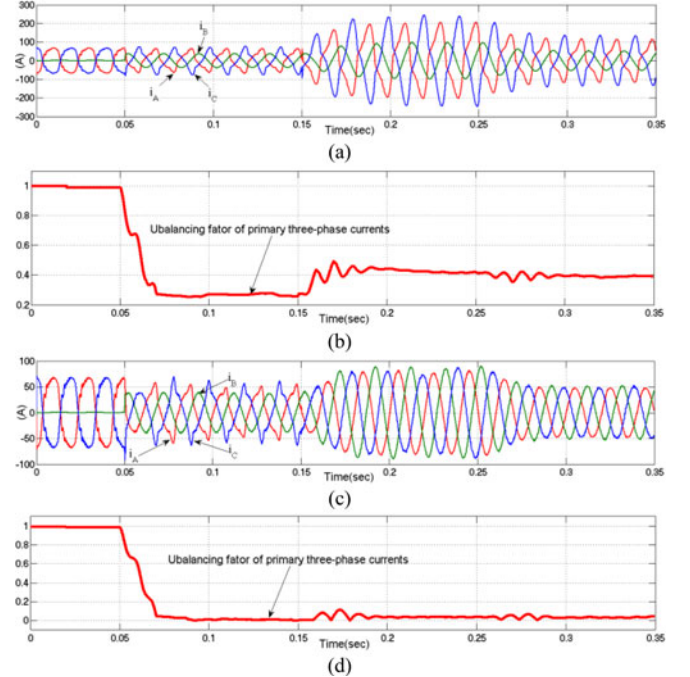


Fig. 21. Simulation waveforms of RPC and ALC-RPFC when the dc-link voltages decrease. (a) Primary three phase currents of RPC when $V_{dc-L} = 58$ kV. (b) Unbalance factor of primary three phase currents of RPC system when $V_{dc-L} = 58$ kV. (c) Primary three phase currents of ALC-RPFC when $V_{dc-LC} = 38.3$ kV. (d) Unbalance factor of primary three phase currents of ALC-RPFC system when $V_{dc-LC} = 38.3$ kV.

system, its PF is always located into 0.96 ~ 0.97, and without the harmonic pollution. It can be seen from Fig. 14 that the maximum value of $V_{\alpha L}$ is $1.34 V_\alpha$. Similarly, V_{dc-L} should be designed around $1.9V_\alpha$. So, compared with conventional RPC, the power rating of ALC-RPFC reduces 28.9%~41.8%.

Additionally, referring to ΔABO in Fig. 13, and considering an extreme situation of RPC, i.e., $X_L \rightarrow 0$, $V_{L\alpha} \rightarrow 0$, and $V_{\alpha L} \rightarrow V_\alpha$. If $I_{c\alpha} = I_{cam}$, the normal apparent power of con α

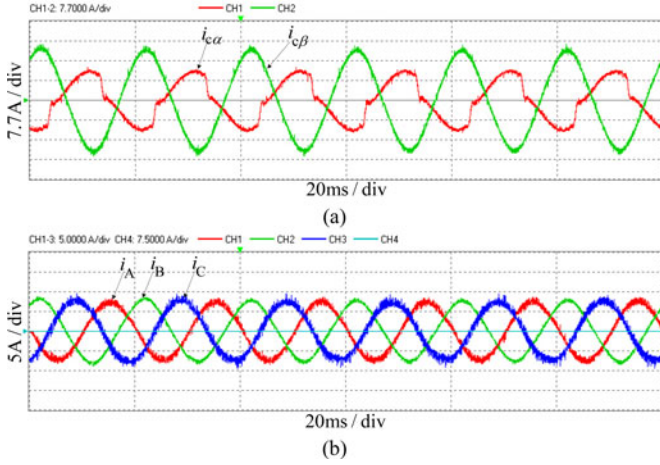


Fig. 25. Steady-state current waveforms of ALC-RPFC when $V_{dc-LC} = 490$ V. (a) Compensating currents. (b) Primary three phase currents.

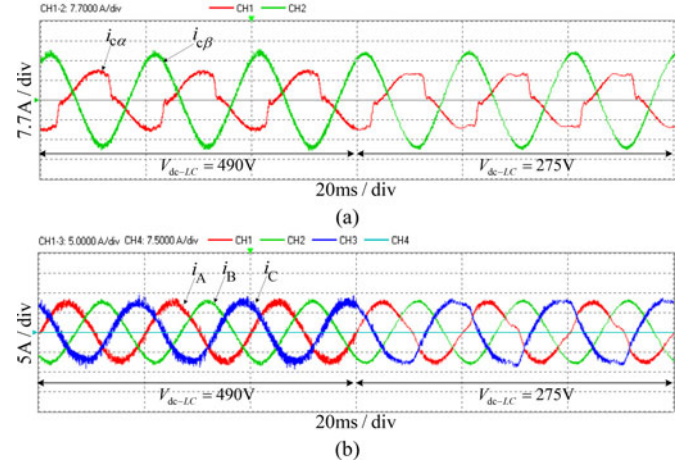


Fig. 27. Dynamic waveforms of ALC-RPFC when V_{dc-LC} decreased from 490 to 275 V. (a) Compensating currents. (b) Primary three phase currents.

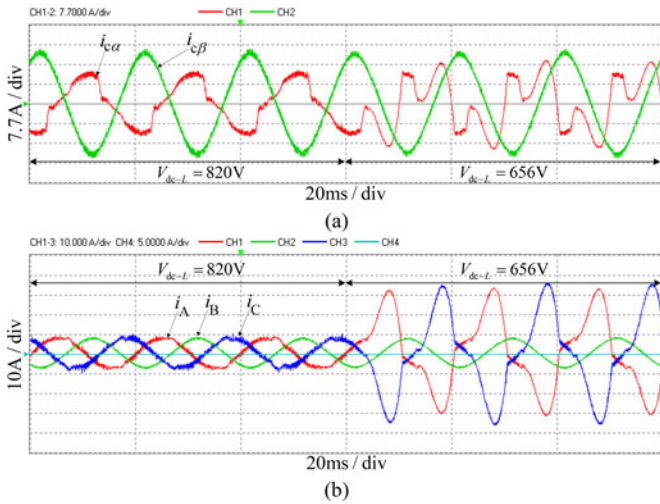


Fig. 26. Dynamic waveforms of RPC when V_{dc-L} decreased from 820 to 656 V. (a) Compensating currents. (b) Primary three phase currents.

margin for the compensating system. Then the original design parameters are selected as

$$\begin{cases} I_{L-95\%(U)} = 2I_{L\alpha-95\%(U)} = 566 \text{ A}, I_{L-95\%(L)} \\ \quad = 2I_{L\alpha-95\%(L)} = 220 \text{ A} \\ V_{dc-LC} = 1.34 V_{\alpha} = 38.9 \text{ kV}, V_{dc-L} = 2.3 V_{\alpha} \\ \quad = 66.7 \text{ kV}, \lambda_{95\%(U)} = 0.9 \end{cases} \quad (22)$$

where $I_{L-95\%(U)}$ and $I_{L-95\%(L)}$ are the upper and lower 95%-probability value of I_L , respectively; V_{dc-LC} and V_{dc-L} are the designed dc-link voltage of ALC-RPFC and RPC, respectively.

Based on the discussions stated in Section III-V, other parameters are listed in Table II.

Besides the values shown in Table II, L_{β} and C_{β} can also be configured flexibly from the curve shown in Fig. 17 ($L_{\beta} > 0$).

2) *Simulation Results*: The specifications of load currents adopted in the simulation are listed in Table III (measured data), in which, $i_{L\alpha 1}$ and $i_{L\alpha 2}$ are adopted to simulate the light (close to $I_{L-95\%(L)}$) and middle-load working conditions of the TSS,

TABLE V
EXPERIMENT RESULTS IN STEADY STATE

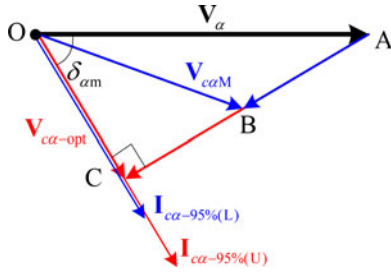
State	λ			THDI/%			$\varepsilon_I / \%^*$
	A	B	C	A	B	C	
Original state	0.45	–	0.96	15.34	–	15.51	97.72
PRC	0.97	0.99	0.98	9.30	6.10	11.21	4.84
ALC-RPFC	0.98	0.99	0.97	7.17	5.44	7.71	5.22

* ε_I is the current unbalancing factor of primary three phase currents.

respectively. Besides, $i_{L\alpha 1} + i_{L\alpha 2}$ is adopted to simulate the heavy-load situation (close to $I_{L-95\%(U)}$). The simulating waveforms are shown in Figs. 18–21.

Compared with the uncompensated waveforms shown in Fig. 18, it can be observed from Figs. 19 and 20 that the primary three-phase currents are tend to be the sinusoidal waveforms with $\text{PF} \approx 1$, and the feed's voltage increases obviously when both systems work in heavy-load situation. It validates the good compensating performance of RPC and ALC-RPFC; although the harmonic compensating performance of RPC is slightly worse than that of ALC-RPFC in the heavy-load case [see Fig. 19 (b)]. However, the power rating of ALC-RPFC is much less than RPC, because $V_{dc-LC} = 38.9$ kV, which is 58.3% of V_{dc-L} (66.7 kV).

It can be seen from Fig. 21(a) and (b) that, the conventional RPC shows a worse heavy-load compensating performance when V_{dc-L} decreases 13% (i.e., $V_{dc-L} = 58$ kV). However, when V_{dc-LC} decreases from 38.9 to 38.3 kV, ALC-RPFC's compensating performance is almost unchanged in heavy-load working condition [see Fig. 21(c) and (d)]. Except that a small amount of harmonics are not eliminated completely in light-load working condition (in fact, they are attenuated by S_d). This shows that the heavy-load compensating performance of ALC-RPFC is much better than that of RPC.


 Fig. 28. Phasor diagram of $\text{con}\alpha$ when OVDM is adopted.

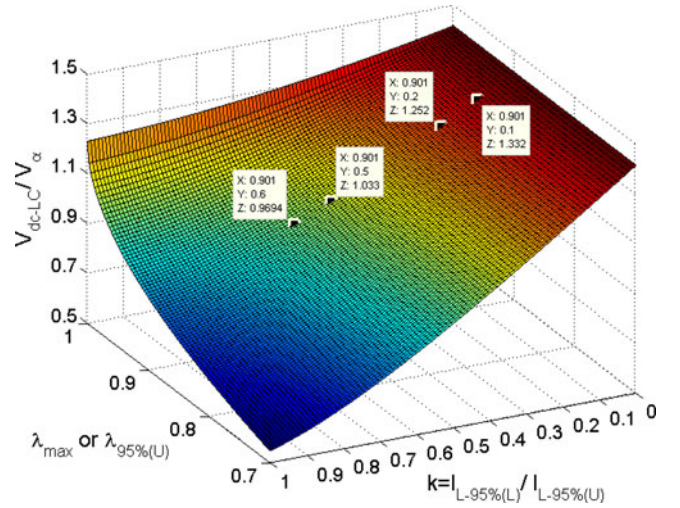
B. Experiment

For further validation of the proposed system, the physical platforms of RPC and ALC-RPFC have been built in a laboratory. The wiring diagram of this setup is shown in Fig. 22. The power rating of the main transformer with turn ratio of 380 V: 380 V and 380 V: 127 V is 40 kVA. The SCR-controlled RL load is adopted to simulate the locomotive with the normal apparent power of 3.8 kVA and $\text{PF} \approx 0.85$.

Four voltage and current signals through A/D converter are measured as the input of TMS320F2812 DSP. v_A provides the synchronous signal for the whole control system. The detection and control algorithms mentioned in Section IV-C are carried out in DSP for digital implementation. The event manager of the DSP emits eight PWM signals through the driver unit as the control signal for two H-bridge converters. Besides, the sample frequency is selected as 12.8 kHz, the scale of IGBT is 1200 V/450 A. Other experiment parameters are listed in Table IV; HIOKI-3196 power quality analyzer is used for data acquisition. The experiment results are shown in Figs. 23–27 and Table V.

The current waveforms of RPC and ALC-RPFC are shown in Figs. 24 and 25, respectively, their experimental data are listed in Table V. Compared with the uncompensated waveforms shown in Fig. 23, the results shown in Figs. 24 and 25 further verify the satisfactory compensating performance of RPC and ALC-RPFC; however, $V_{\text{dc-LC}} = 490$ V, which is 59.8% of $V_{\text{dc-L}} (820$ V). The result further validates the good power rating saving ability of ALC-RPFC.

In addition, it can be seen from the dynamic waveforms shown in Figs. 26 and 27, that if the dc-link voltage of RPC decreases by 20% to 656 V (it is still larger than the feeder's peak voltage $380\sqrt{2}$ V), the compensating performance turns bad (see Fig. 26). However, it can be seen from Fig. 27, that when the dc-link voltage of ALC-RPFC decreases from 490 to 275 V (reducing ratio is 44%), the compensating performance of ALC-RPFC almost unchange. If the load current in experimental situation corresponds to the heaviest working condition of a traction network (i.e., $I_{LM} = 9.8$ A, $\lambda_{\text{max}} = 0.85$), the aforementioned experiment results also indicate that the power quality problems in most heavy-load cases can be compensated by ALC-RPFC when $V_{\text{dc-LC}}$ is designed at 490 V. Also, the dynamic results further validate the effectiveness of the ALC-RPFC's ability on decreasing the power capacity.


 Fig. 29. Relationship among $V_{\text{dc-LC}}/V_\alpha$, k , and λ_{max} (or $\lambda_{95\%}(U)$).

VII. CONCLUSION

This paper proposed an asymmetric double LC -coupled railway power conditioner for single-phase ac electric railway supply system. At first, its operating property under fluctuated load condition is analyzed in detail. To meet the demand of practical applications for the “intense and random” load of electrical railway power system, we proposed a systematic design method for LC -coupling branches, and the corresponded power capacity analysis method for the purpose of determining the design range of ALC-RPFC's dc-link voltage. Finally, simulation and experiment results validate these conceptions.

ALC-RPFC fully explores the potentials of two asymmetric passive LC branches. In comparison to conventional RPC, it has excellent heavy-load compensating ability with lower dc-link voltage. Besides, all the parameters' design methods proposed in this paper are based on the fluctuated electrical railway working condition, and they are also useful for industrial applications. Therefore, the proposed conditioner is an industrial effective electric railway compensating system with high cost-efficiency and high reliability.

APPENDIX A

Fig. 28 shows the phasor diagram of $\text{con}\alpha$ when OVDM is adopted. In Fig. 28, AB and AC is the minimum and maximum voltage drop of $X_{\alpha\text{-opt}}$, respectively, and satisfying

$$\begin{cases} AB = |X_{\alpha\text{-opt}}| I_{c\alpha-95\%(L)} \approx |X_{\alpha\text{-opt}}| \varepsilon_{\text{aver}} I_{L-95\%(L)} \\ AC = |X_{\alpha\text{-opt}}| I_{c\alpha-95\%(U)} \approx |X_{\alpha\text{-opt}}| \varepsilon_{\text{aver}} I_{L-95\%(U)} \end{cases} \quad (\text{A1})$$

where $I_{c\alpha-95\%(U)}$, $I_{c\alpha-95\%(L)}$ and $I_{L-95\%(U)}$, $I_{L-95\%(L)}$ are the upper and lower 95%-probability value of $I_{c\alpha}$ and I_L , respectively.

From Fig. 28, $V_{c\alpha m}$ is the maximum output voltage of $\text{con}\alpha$. By using the cosine theorem in $\triangle ABO$ and combining (13), $V_{c\alpha m}$ can be calculated as

$$V_{c\alpha M} = V_{\alpha} \sqrt{\varepsilon_{\text{aver}}^2 \xi_1^2 k^2 - 2\varepsilon_{\text{aver}} \xi_1 k \sin \delta_{\alpha m} + 1} \quad (\text{A2})$$

where $k = I_{L-95\%}(L) / I_{L-95\%}(U)$.

Considering the designed dc-link voltage of ALC-RPFC $V_{\text{dc-LC}}$ should satisfy

$$V_{\text{dc-LC}} = \sqrt{2} V_{c\alpha M}. \quad (\text{A3})$$

Combining (A.2), (A.3), and (12), we can obtain Fig. 29.

In practical situation, k and λ_{max} (or $\lambda_{95\%}(U)$) are always located in $0.2 \sim 0.5$ and $0.85 \sim 0.93$, respectively. It can be seen from Fig. 29 that, a good compensating performance can be obtained when the designed dc-link voltage of ALC-RPFC is selected as $1.1 \sim 1.35 V_{\alpha}$.

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