DC-Link Voltage Reduction Design Method for Three-Phase Four-Wire LC-Hybrid Active Power Filters Under Reactive and Unbalanced Current Compensation

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***Abstract*— Previously, the required dc-link voltage of the three-phase four-wire (3P4W) LC- coupling hybrid active power filter (LC-HAPF) was developed based on balanced loading condition. To extend its operation into unbalanced loading cases, this paper presents a general mathematical deduction of the LC-HAPF required dc-link voltage through the circuit models in zero-, positive- and negative-sequence (0-1-2 coordinate). However, a significant high dc-link voltage will be required to compensate both reactive and unbalanced currents when the coupling LC part is designed based on the original method. Thus, the LC-HAPF will lose its key benefit with low dc-link operating voltage, and increasing the system initial cost, switching loss and switching noise. In this paper, a novel coupling LC design method is proposed to effectively reduce the LC-HAPF dc-link voltage, which is based on the considerations in both reactive and unbalanced currents. Finally, representative simulation results of the 3P4W LC-HAPF for reactive and unbalanced currents compensation are given to verify the correctness and effectiveness of the proposed deduced and designed methods.**

***Keywords*— DC-Link, hysteresis current control, active power filter (APF), hybrid active power filter (HAPF), unbalanced current, reactive power, pulse width modulation (PWM).**

I. INTRODUCTION

In typical three-phase four-wire (3P4W) distributed power systems, asymmetric loads exist pervasively like large furnaces, rectifiers and fluorescent lamp etc, which will produce abundant unbalanced currents. Although the unbalance is a common occurrence in the 3P4W distributed power system, it can be harmful to the safe operation of the power network, reliability and stability. Moreover, the power losses distributed network can vary significantly depending on the loading unbalance [1]. In order to reduce this kind of power losses, the compensation to the unbalanced current is a necessary aspect.

In addition, the reactive power issue in the distributed power network takes a large portion of the power quality problems. Researchers in [2]-[7] proposed different kinds of power filter topology to compensate the reactive power, including capacitor blanks, static var compensators (SVC), LC coupling hybrid active power filters (LC-HAPF), etc. In [8]-[10], the dynamic reactive power compensation control algorithms for the LC-HAPF were proposed, the required inverter's dc-link voltage was calculated according to the instantaneous reactive power consumption by the loads. Thus, the operating switching loss of the LC-HAPF can be minimized by applying the calculated required dc-link voltage.

However, the required dc-link voltage for the LC-HAPF in [8] was deduced in a-b-c coordinate and is calculated based on the loading reactive power in each phase independently. When there exist unbalanced current components in the system, the calculated dc-link voltage cannot eliminate those unbalanced currents among phases, thus the three-phase system currents remain unbalanced after compensation. Due to the limitations among the existing literatures, all dc-link voltage analyses of the LC-HAPF in [8]-[10] are under balanced loading cases, and less literature has been discussed both reactive and unbalanced current compensation issues for the LC-HAPF.

In this paper, a mathematical deduction for the LC-HAPF required dc-link voltage is proposed under unbalanced loading condition. To consider the unbalanced current components, the computation of the required dc-link voltage in zero-, positive- and negative-sequence (0-1-2 coordinate) is introduced, and the calculated dc-link voltage is just sufficient to compensate both reactive and unbalanced currents effectively under 3P4W unbalanced linear loadings.

In addition, the design for the coupling LC passive part of the LC-HAPF was normally based on reactive power consumption by the load (i.e. the reactive current consumption in 1-sequence), then most portion of reactive power are compensated by the passive part, thus reducing the burden and rating of the active inverter part and providing a cost effective compensating solution for the LC-HAPF [5]-[10]. However, under unbalanced loading condition, it is being found that the required dc-link voltage can be quite high when the coupling

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LC is still designed according to the original method mentioned above. The switching devices likes IGBTs will endure a higher voltage stress, thus the operating switching losses will increase and even shorten the lifetime of switching devices [11-12]. Moreover, the high dc-link voltage may even exceed the original designed voltage limit, thus a higher rating and costly switching devices should be replaced. Therefore, a novel coupling LC design method is proposed in this paper to reduce the dc-link voltage requirement under both reactive and unbalanced currents compensation considerations, in which the coupling capacitance is designed based on both reactive current in 1-sequence and unbalanced currents in 0- and 2-seuqence.

II. Calculation of Required DC-Link Voltage under Unbalanced Loading

A. Three-Phase Four-Wire LC-HAPF Modeling in 0-1-2 Coordinate

Fig. 1 shows the circuit structure of a three-phase four-wire (3P4W) center-split LC-HAPF under three-phase unbalanced inductive linear load. In the following, all the analyses will be considered at fundamental frequency, which will be denoted by the subscript "*f*". The corresponding AC circuit analysis in Root Mean Square (RMS) value between the source and compensator is shown in Fig. 2, where V_{fx} (the subscript $x=a,b,c$) represents the three-phase system voltage at point of coupling (PCC); I_{fCx} represents the three-phase compensating current and I_{fCn} is the neutral compensating current; C_C and L_C represent the coupling LC capacitance and inductance of the 3P4W LC-HAPF, in which their coupling impedance are equal to each other among three phases, i.e. $X_{fLCca} = X_{fLCcb} = X_{fLCcc} = X_{fLCc}$; V_{finvx} represent the three-phase inverter voltage. To consider the unbalanced components, the LC-HAPF circuit model in a-b-c coordinate as shown in Fig. 2 is transformed into 0-1-2 coordinate. By applying the symmetrical component theory, the 0-, 1-, 2-sequence circuit models for the 3P4W LC-HAPF can be redrawn as Fig. 3. Where the subscript $y=0,1,2$ represents the three-phase in 0-1-2 sequence.

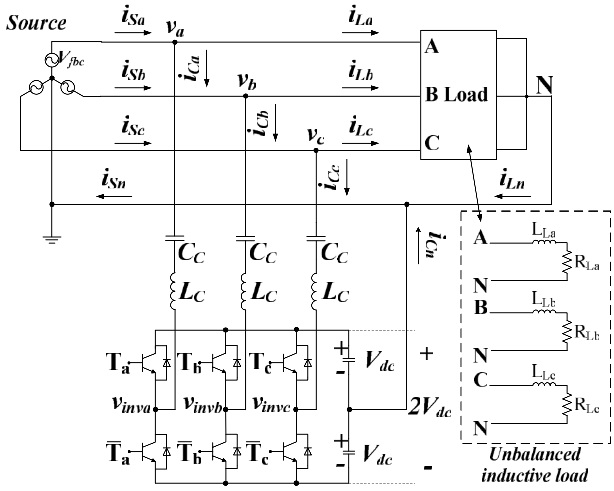


Fig. 1 Circuit structure of the 3P4W center-split LC-HAPF.

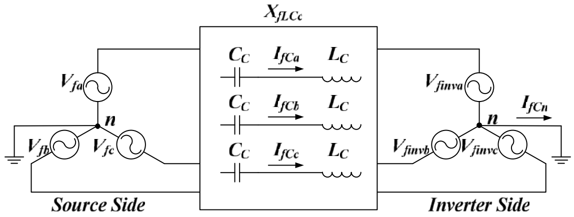


Fig. 2 a-b-c circuit model of the 3P4W LC-HAPF in RMS value.

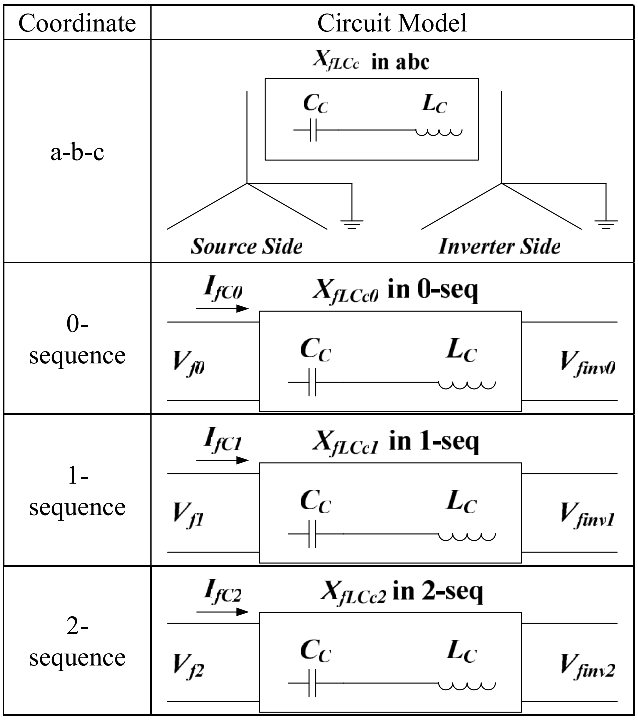


Fig. 3 0-, 1- and 2-seuqence circuit models of the 3P4W LC-HAPF.

From Fig. 3, the coupling LC impedance of the LC-HAPF in 0-1-2 sequence can be deduced as:

$$\mathbf{X}_{fLCc}^{012} = \mathbf{A}^{-1}\mathbf{X}_{fLCc}^{abc}\mathbf{A} \tag{1}$$

where $$\mathbf{A}^{-1} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \mathbf{A} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{2}$$

$$\mathbf{X}_{fLCc}^{012} = \begin{bmatrix} X_{fLCc} & 0 & 0 \\ 0 & X_{fLCc} & 0 \\ 0 & 0 & X_{fLCc} \end{bmatrix} = \mathbf{X}_{fLCc}^{abc} \tag{3}$$

From Eq. (3), the coupling LC impedance X_{fLCc} holds consistency between a-b-c and 0-1-2 coordinates. Moreover, the impedance of the coupling capacitor at fundamental frequency X_{fCc} is usually much higher than that of coupling inductor X_{fLc} for the LC-HAPF. Thus, the overall coupling impedance of the LC-HAPF shows capacitive at fundamental frequency.

$$\left|X_{fCc}\right| >> \left|X_{fLc}\right| \quad (4)$$

$$X_{fLCc} = \left|\frac{1}{\omega C_C} - \omega L_C\right| \angle 270^\circ \quad (5)$$

According to the circuit models in Fig. 3, the required inverter voltages for the 3P4W LC-HAPF in 0-1-2 coordinate can be computed by Eq.(6) – Eq. (8), where the system voltage V_{f0} and V_{f2} in 0- and 2-sequence are zero due to the balanced supply voltage assumption and simplification.

$$\text{0-seq.} \quad V_{finv0}\angle\theta_{V_{finv0}} = -\left|X_{fLCc}\right|\left|I_{fC0}\right|\angle\left(270^\circ + \theta_{I_{fC0}}\right) \quad (6)$$

$$\text{1-seq.} \quad V_{finv1}\angle\theta_{V_{finv1}} = \left|V_{f1}\right|\angle 0^\circ - \left|X_{fLCc}\right|\left|I_{fC1}\right|\angle\left(270^\circ + \theta_{I_{fC1}}\right) \quad (7)$$

$$\text{2-seq.} \quad V_{finv2}\angle\theta_{V_{finv2}} = -\left|X_{fLCc}\right|\left|I_{fC2}\right|\angle\left(270^\circ + \theta_{I_{fC2}}\right) \quad (8)$$

B. Deduction of Required DC-Link Voltage

In [8], the mathematical deduction for the LC-HAPF required dc-link operating voltage was discussed in detail in a-b-c coordinate, in which the dc-link voltage was calculated based on the loading reactive power in each phase independently. And the aim for the LC-HAPF was to compensate the reactive power in a, b and c phases independently. However, under unbalanced loading cases, this computation method ignored the unbalanced currents, the calculated required dc-link voltage cannot eliminate those unbalanced components among phases, thus the three-phase source currents were remain unbalanced after compensation by the LC-HAPF. As a result, a significant neutral current could appear in the 3P4W system.

In this paper, the mathematical deduction for the LC-HAPF required dc-link voltage under both reactive power and unbalanced currents considerations is proposed. According to the circuit models in Fig. 3, the required inverter voltages for the LC-HAPF in 3P4W circuit structure in 0-1-2 coordinate can be obtained by Eq. (6) – Eq. (8). In which, the corresponding fundamental compensating currents are obtained by the loadings and can be expressed as Eq. (9).

$$\begin{bmatrix} I_{fC0}\angle\theta_{I_{fC0}} \\ I_{fC1}\angle\theta_{I_{fC1}} \\ I_{fC2}\angle\theta_{I_{fC2}} \end{bmatrix} = -\begin{bmatrix} I_{fL0}\angle\theta_{I_{fL0}} \\ I_{fL1}\sin\theta_{I_{fL1}}\angle 90^\circ \\ I_{fL2}\angle\theta_{I_{fL2}} \end{bmatrix} \quad (9)$$

where $I_{fL1}\sin\theta_{I_{fL1}}$ represents the loading fundamental reactive current in 1-seuqence.

Moreover, the coupling impedance X_{fLCc} in Eq. (6) – Eq. (8) is determined by the designed method in [8] , where the coupling LC part is designed to deal with the reactive current component, i.e. the reactive current component in 1-sequence, thus minimizing the inverter output voltage in 1-sequence. When the coupling inductance L_C is designed to ensure the output current ripple of the inverter, the coupling capacitance C_C can be computed as Eq. (10).

$$C_C = \frac{1}{2\pi f\left(\dfrac{V_{f1}}{I_{fL1}\sin\theta_{fI_{L1}}} + 2\pi f L_C\right)} \quad (10)$$

After the required inverter voltages in 0-1-2 coordinate were obtained by Eq. (6) – Eq. (8), the three-phase inverter voltage in a-b-c coordinate can be recalculated from 0-1-2 coordinate by applying symmetrical component theory as in Eq. (11) and Eq. (12). Finally, when the modulation index m is assumed as m ≈ 1, the required reference dc-link voltage V_{dc_req} equals to the peak of the maximum inverter fundamental voltage $V_{finvmax}$ in a-b-c coordinate, which can be expressed as in Eq. (13) and Eq. (14).

$$V_{finv}^{abc} = \mathbf{A}^{-1} V_{finv}^{012} \quad (11)$$

$$\begin{bmatrix} V_{finva}\angle\theta_{V_{finva}} \\ V_{finvb}\angle\theta_{V_{finvb}} \\ V_{finvc}\angle\theta_{V_{finvc}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{finv0}\angle\theta_{V_{finv0}} \\ V_{finv1}\angle\theta_{V_{finv1}} \\ V_{finv2}\angle\theta_{V_{finv2}} \end{bmatrix} \quad (12)$$

$$V_{finv\max} = MAX(V_{finva}, V_{finvb}, V_{finvc}) \quad (13)$$

$$V_{dc\_req} = \sqrt{2} V_{finv\max} \quad (14)$$

C. Simulation Verification for the Proposed Required DC-Link Voltage Deduction

In this part, simulation studies are carried out on a 3P4W LC-HAPF to verify the deduced required dc-link voltage for both reactive and unbalanced currents compensation. The unbalanced loading parameter values are given in Table I.

For the impedance of the coupling LC, when L_C=20mH is designed for limiting the current ripple generated by the inverter, the calculated C_C=130uF based on system voltage V_{f1} = 220V, 1-sequence load current I_{fL1} = 18.19A, angle difference between the system voltage and load current $\theta_{fI_{L1}}$ = 44.2º and fundamental frequency f=50Hz. By substituting the loading parameters from Table I into Eq. (6) – Eq. (14), the required dc-link voltage can be computed as V_{dc_req}=540V.

Fig. 4 shows the load-side three-phase and neutral current waveforms, and the corresponding characteristics are summarized in Table II, including phase current rms I_{Lx_rms}, phase reactive power Q_{fLx}, phase power factor PF_{fLx}, phase current total harmonic distortion THD_{iLx}, and current unbalanced index UBI_{fL}.

To verify the correctness of the required dc-link voltage deduction for LC-HAPF to compensate both reactive and unbalance currents, two simulations are conducted: (i) the compensating performance of the LC-HAPF with insufficient dc-link voltage V_{dc}=500V<V_{dc_req}; (ii) the compensating performances of the LC-HAPF with sufficient dc-link voltage

V_{dc}=600V>V_{dc_req}. Fig. 5(a) and (b) show the source current waveforms after compensation by the LC-HAPF under the above two conditions, and the compensating performances are summarized in Table III. From the simulation results, a satisfactory compensation is achieved if the applied dc-link voltage is higher than the required one (V_{dc}>V_{dc_req}), while a poor compensation will occur in phase A if the applied dc-link voltage is lower than the required one (V_{dc}<V_{dc_req}).

Table I Unbalanced Loading Parameters

a-b-c coordinate				0-1-2 coordinate	
Phase	R_L (ohm)	L_L (mH)	I_{Lrms}	Sequence	I_{Lrms}
A	3.5	14.5	38.3∠94.0	0	10.2∠-59.7
B	22.5	35	8.8∠-146.0	1	18.2∠-44.2
C	22.5	35	8.8∠-52.4	2	10.2∠-59.7

Table II Characteristics of the Unbalanced Loading Before LC-HAPF Compensation

Before LC-HAPF Compensation for Testing Loading						
Phase	I_{Lx_rms} (A)	I_{Ln_rms} (A)	Q_{fLx} (var)	PF_{fLx}	THD_{iLx} (%)	UBI_{fL} (%)
A	38.3	30.7	6672	0.61	0.0	105.6
B	8.8		848	0.90	0.0	
C	8.8		848	0.90	0.0	

Table III LC-HAPF Compensating Performance with V_{dc}=500V and V_{dc}=600V for V_{dc_req}=540V

After LC-HAPF Compensation for Testing Loading							
V_{dc} (V)	Phase	I_{Lx_rms} (A)	I_{Ln_rms} (A)	Q_{fLx} (var)	PF_{fLx}	THD_{iLx} (%)	UBI_{fL} (%)
500V (Insufficient)	A	11.0	15.2	2344	0.26	63.9	12.7
	B	13.4		-50	1.00	0.9	
	C	13.4		-54	1.00	1.1	
600V (Sufficient)	A	12.3	1.4	82	1.00	2.8	5.6
	B	13.5		-48	1.00	1.7	
	C	13.4		-64	1.00	1.8	

Notes: the shaded area means unsatisfactory results

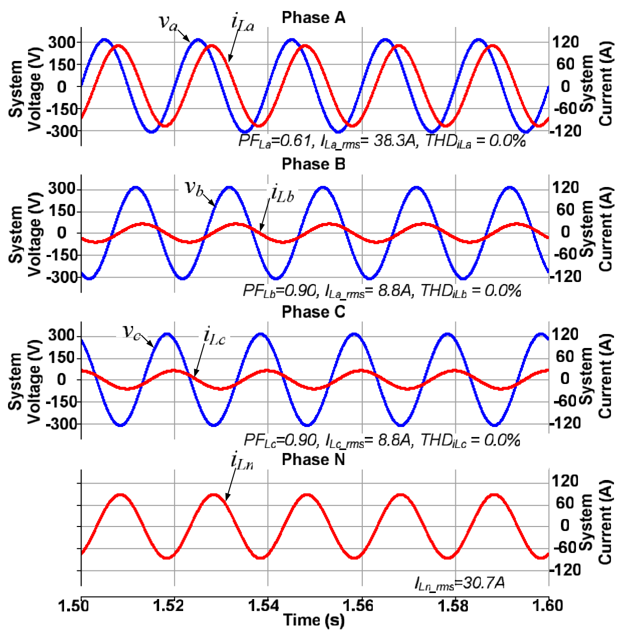


Fig. 4 Unbalanced loading simulation waveforms

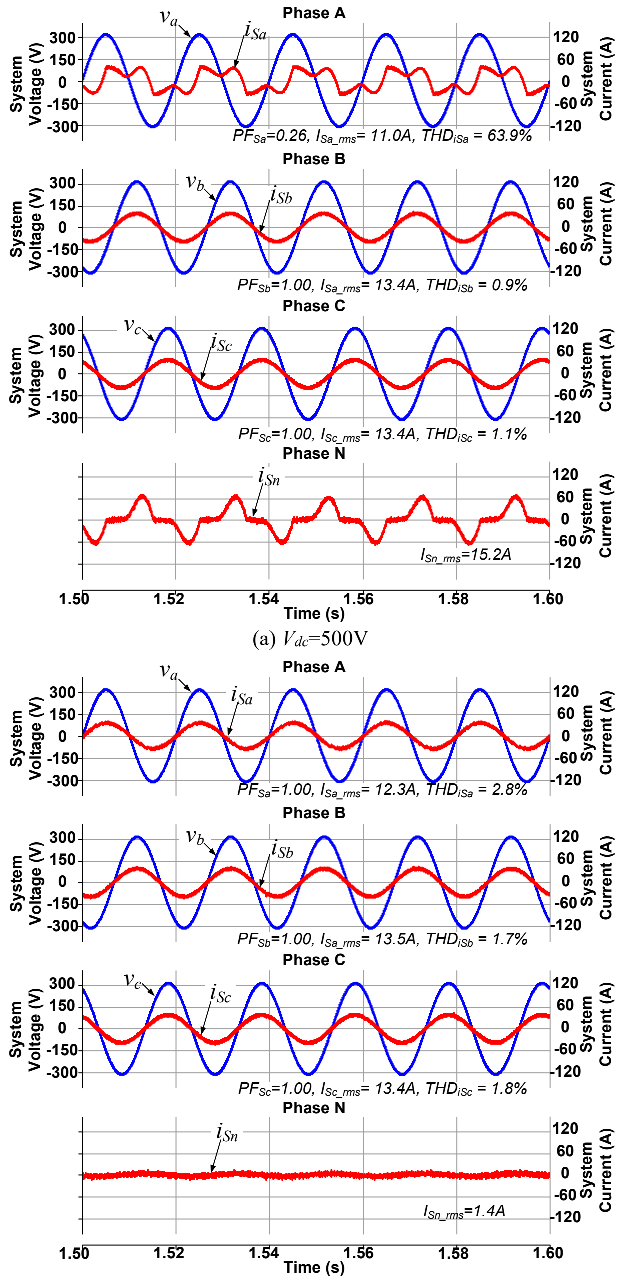


Fig. 5 LC-HAPF compensating performance with (a) insufficient applied dc-link voltage V_{dc}<V_{dc_req}; (b) sufficient applied dc-link voltage V_{dc}>V_{dc_req}.

III. Proposed LC-HAPF Parameter Design for DC-Link Voltage Reduction

From Section II, the required dc-link voltage of the LC-HAPF for compensating both reactive and unbalanced currents have been deduced and verified. However, a relatively high dc-link voltage is required to obtain a satisfactory compensation. With a high dc-link voltage, the voltage source inverters (VSIs) become bulky, and the ratings of the switches used in the VSI should be increased, a high switching loss is also endured. Moreover, the required dc-link voltage is much higher than the system voltage, thus losing the key benefit of the LC-HAPF topology, i.e. the cost-effective solution with low dc-link voltage [5]-[10]. In this paper, a novel coupling

LC design method is proposed to avoid high dc-link voltage requirement during LC-HAPF unbalanced loading compensation.

Under balanced inductive loading condition, as the compensated current component only flows in 1-sequence circuit, the design of coupling LC part is aimed at compensating the reactive current in 1-sequence, thus minimize the dc-link voltage. However, under unbalanced loading condition, there are additional compensating current components flowing into 0- and 2-seuqence circuits. Therefore, the coupling LC design method proposed in [8]-[10] cannot achieve minimum dc-link voltage operation for the LC-HAPF. To provide a lower inverter's dc-link voltage under unbalanced loading condition, the coupling LC design should consider all symmetrical components including 0- , 1- and 2-sequence circuits instead of considering the 1-sequence circuit only.

From Eq. (6) – Eq. (8), the magnitude of the required inverter voltages are given in 0-1-2 coordinate, where V_{finv1} is used for reactive current compensation in 1-seuqence, and V_{finv0} and V_{finv2} are used for unbalanced currents compensation. Thus, the required dc-link voltage can be reduced by reducing the magnitude of these inverter voltages. Assume that the three-phase unbalanced loading keeps constant for a variety of time, V_{finv0} and V_{finv2} can be reduced by decreasing the impedance of the coupling LC at 0- and 2- sequences. On the other hand, to reduce V_{finv1}, the voltage drops on the coupling LC should be designed as close as the source voltage in 1-seuqence.

Thus, V_{dc_req} can be expressed as a function of the C_C, and the relationship between V_{dc_req} and C_C under the loading condition listed in Table I can be plotted as Fig. 6. In Fig. 6, there is an optimal design of the coupling LC part to minimize the required inverter voltage in 0-1-2 coordinate and achieving minimum dc-link voltage operation under reactive power and unbalanced current compensation.

In Fig. 6, the x-axis represents the coupling capacitance C_C, while the y-axis represents the required dc-link voltage V_{dc_req} for both reactive power and unbalance currents compensation under the unbalanced loading condition listed in Table I. From Fig. 6, it is clearly shown that there is a minimum dc-link voltage operating point for the LC-HAPF when C_C is changed to C_C=180uF. Moreover, the required dc-link voltage is reduced from V_{dc_req}=540V with C_C=130uF (at operating point A) to V_{dc_req}=260V with C_C=180uF (at operating point B).

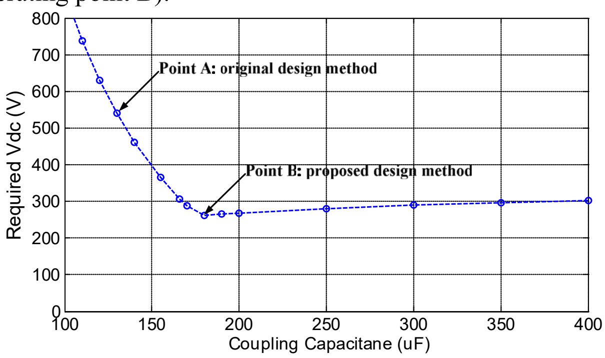
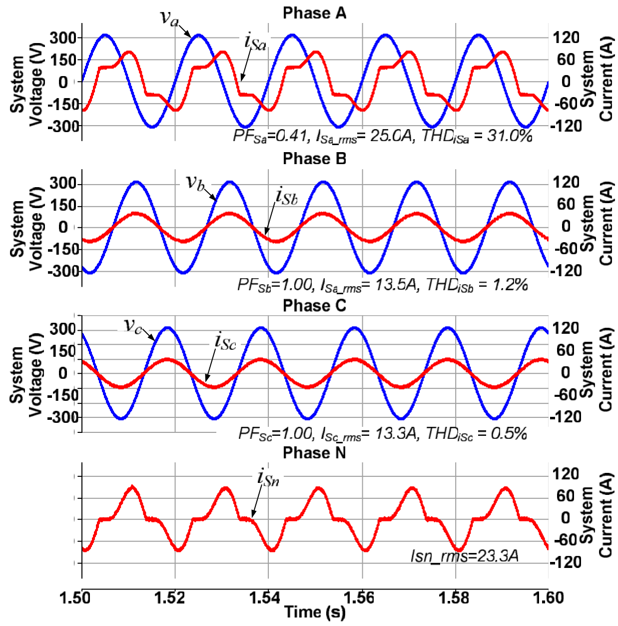


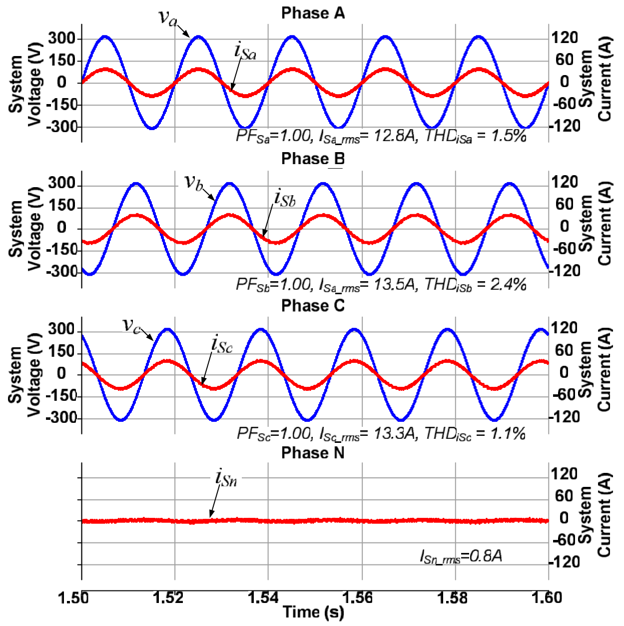
Fig. 6 Relationship between the required V_{dc} and coupling C_c for LC-HAPF

IV. Simulation Verification for the Proposed LC-HAPF Parameter Design for DC-Link Voltage Reduction

In order to show the effectiveness of the proposed design LC method, the compensating performance at V_{dc}=300V with the original coupling C_C=130uF value is provided for comparison. Fig. 8(a) shows the compensating performance of the LC-HAPF by using the original coupling LC design method [15], and Fig. 8(b) shows the compensating performance of the LC-HAPF by using the proposed coupling LC design method, and the corresponding results are summarized in Table IV. From Fig. 8(a), Fig. 8(b) and Table IV, the simulation results clearly show that there is an improvement by applying the proposed LC designed method with the same operating dc-link voltage V_{dc}=300V. Moreover, compared to the results with the original coupling LC design method in Fig. 5(b) and Table III with V_{dc}=600V, both simulation results are more or less the same, but the simulation results with the proposed design method can achieve a much lower dc-link voltage requirement (V_{dc_req}=260V). Therefore, it is clearly verified that the dc-link voltage can have a great reduction from V_{dc_req} =540V to V_{dc_req} =260V when applying the proposed design method with the coupling capacitance is redesigned from C_C =130uF to C_C =180uF.



(a) Orignal design method



(b) Proposed design method

Fig. 8 LC-HAPF compensating performances at V_{dc}=300V by applying (a) original design method with C_C=130μF; (b) proposed design method with C_C=180μF

Table IV LC-HAPF Compensating Performance with Original design Method and Proposed Design Method PF_{fS} =1.00

After LC-HAPF Compensation for Testing Loading								
Design Method	Phase	V_{dc} (V)	I_{Sx_rms} (A)	I_{Sn_rms} (A)	Q_{fSx} (var)	PF_{fSx}	THD_{iSx} (%)	UBI_{fS} (%)
Original with C_C=130uF	A	300	25.0	23.3	5021	0.41	31.0	44.8
	B		13.5		-32	1.00	1.2	
	C		13.3		-28	1.00	0.5	
Proposed with C_C=180μF	A	300	12.8	0.8	58	1.00	1.5	3.0
	B		13.5		-20	1.00	2.4	
	C		13.3		-31	1.00	1.1	

Notes: the shaded area means unsatisfactory results

V. Conclusion

In this paper, the operation of the 3P4W LC-HAPF is extended into unbalanced loading conditions. The analytical expressions of the 3P4W LC-HAPF required dc-link voltage are derived through 0-1-2 coordinate for compensating both reactive and unbalanced currents. To avoid the high dc-link operating voltage requirement, the coupling LC of the LC-HAPF should be designed based on both reactive current component (full- and over-compensation) in 1-sequence and the unbalanced current component in 0- and 2-sequence. The required dc-link voltage deductions and novel coupling LC design method are verified by detailed simulations.

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