Minimum DC-Link Voltage Design of Three-Phase Four-Wire Active Power Filters

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***Abstract*—This paper presents a minimum dc-link voltage design for three-phase four-wire center-split active power filters (APFs). According to the current quality data and the APF single-phase equivalent circuit models, the minimum dc-link voltage expression for the APF is deduced and proposed, in which the deduced expression is applicable to single-phase and three-phase four-wire APF systems. Representative simulation results of the three-phase four-wire APF are presented to verify the minimum dc-link voltage expression.**

Keywords-Active power filters, dc-link voltage, passive power filters.

I. INTRODUCTION

With the proliferation and development of power electronics equipments (nonlinear loads) in utility power system, power quality issues become more serious, especially in harmonic current, harmonic neutral current and reactive power problems. High current harmonic distortion causes various problems in both distribution systems and consumer products, such as equipment overheating, blown capacitor fuses, mal-operation of the protection devices, transformer overheating, etc. [1], [2]. Excess neutral current will overheat and even burn the neutral conductor. In addition, the larger the reactive current/power, the larger the system losses and lower the network stability. Due to these reasons, electrical utilities usually charge the industrial and commercial customers a higher electricity cost with low power factor situation.

In order to eliminate those current quality problems, power filters can be implemented. Since the first installation of passive power filters (PPFs) in the mid 1940's, PPFs have been widely used to suppress harmonic current and compensate reactive power in distribution power systems [3] – [6] due to their low cost, simplicity and high efficiency characteristics. Unfortunately, they have many disadvantages such as low dynamic performance, filtering characteristics easily be affected by small variations of the system parameter values, and resonance problems [3] – [5]. Since the concept "Active ac Power Filter" was first developed by L. Gyugyi in 1976 [6], the research studies of the active power filters (APFs) for current quality compensation are prospering since then, in which APFs can overcome the above mentioned disadvantages inherent in PPFs. However, due to the limitations among the existing literatures, there is still no mathematical deduction for the design of the APF minimum dc-link voltage in current harmonics and reactive power compensation. Therefore, this paper aims to investigate and discuss the minimum dc-link voltage design for a three-phase four-wire APF.

In the following, a transformerless two-level three-phase four-wire center-split APF and its corresponding single-phase fundamental and harmonic equivalent circuit models are initially introduced in Section II. According to the current quality of the loading and the APF single-phase equivalent circuit models, the minimum dc-link voltage expression for the APF is proposed in Section III. Finally, representative simulation results of the three-phase four-wire center-split APF are given to verify its minimum dc-link voltage design expression. Given that most of the loadings in the distribution power systems are inductive, the following analysis and discussion only focus on inductive nonlinear loads [7].

II. SINGLE-PHASE FUNDAMENTAL AND HARMONIC EQUIVALENT CIRCUIT MODELS OF A THREE-PHASE FOUR-WIRE APF

Fig. 1 shows the circuit configuration of the two-level three-phase four-wire center-split active power filter (APF), where the subscript 'x' denotes phase a,b,c,n. v_{sx}, v_x are the system and load voltages, i_{sx}, i_{Lx} and i_{cx} are the system, load and inverter current for each phase. L_c is the coupling inductor of the APF. C_{dc}, V_{dcu} and V_{dcL} are the dc capacitor, upper and lower dc capacitor voltages. In order to simplify the minimum dc-link voltage deduction for the APF, v_{sx} is assumed to be sinusoidal without harmonic component. Moreover, L_s is normally neglected due to its low value relatively, thus $v_{sx} \approx v_x$. Fig. 2 shows the APF single-phase fundamental and harmonics equivalent circuit models, where the subscript 'f' and 'n' denote the fundamental and harmonics frequency components, and $n = 2,3...\infty$. Through these two circuit models, the APF minimum dc-link voltage expression with respect to different loading current quality parameters can be deduced. In the following analysis, all parameters are in root mean square (rms) value.

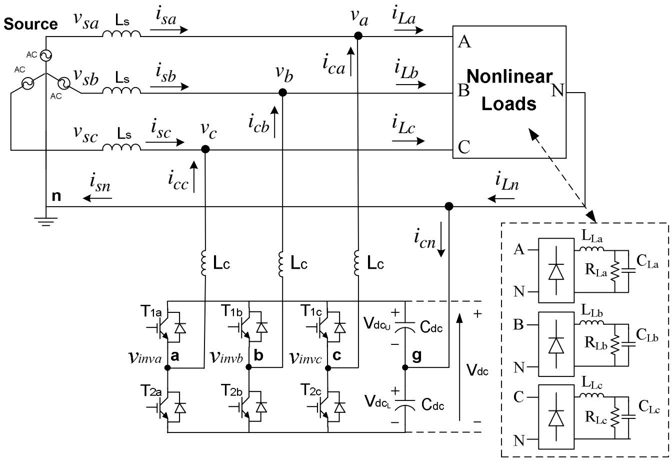


Figure 1. Circuit configuration of the three-phase four-wire center-split APF.

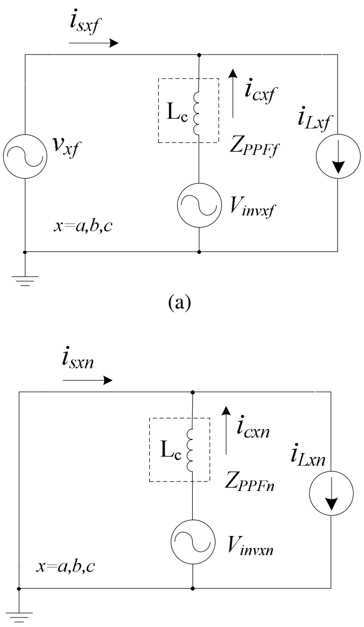


Figure 2. APF single-phase equivalent circuit models at: (a) fundamental frequency, (b) harmonics frequency.

III. MINIMUM DC-LINK VOLTAGE DEDUCTION FOR THE THREE-PHASE FOUR-WIRE APF

Via Fig. 2, the required inverter fundamental output voltage (V_{invxf}) and inverter harmonic output voltage (V_{invxn}) at each harmonic order can be found. As V_{invxf} and V_{invxn} are in rms values, the minimum dc-link voltage values (V_{dcxf}, V_{dcxn}) for compensating the phase fundamental reactive current component and each n^{th} order harmonic current component are calculated as the peak values of the required inverter fundamental and each n^{th} order harmonic output voltages, in which $V_{dcxf} = \sqrt{2}V_{invxf}$, $V_{dcxn} = \sqrt{2}V_{invxn}$. In order to provide sufficient dc-link voltage for compensating load reactive and harmonic currents, the minimum dc-link voltage requirement (V_{dcx}) of the APF single-phase circuit model is deduced by considering the worst phase relation between each harmonic component, in which their corresponding peak voltages of the VSI at AC side are assumed to be superimposed.

$$V_{dcx} = \sqrt{\left|V_{dcxf}\right|^2 + \sum_{n=2}^{\infty}\left|V_{dcxn}\right|^2} \tag{1}$$

From Fig. 2(a), when the voltage load V_x is pure sinusoidal without harmonic components, $V_x = V_{xf}$, the inverter fundamental output voltage of the APF single-phase equivalent circuit model can be expressed as:

$$V_{invxf} = V_x + Z_{PPFf} \times I_{cxf} \tag{2}$$

As the coupling part is a pure inductor L_c, $Z_{PPFf} = \left|X_{Lcf}\right| e^{j\phi f}$, where X_{Lcf} is the fundamental reactance of L_c and $\phi f = 90^{\circ}$. When the APF operates at ideal case, the fundamental compensating current I_{cxf} contains pure reactive component I_{cxfq} only without the active current component I_{cxfp}, therefore (2) can be rewritten as:

$$V_{invxf} = V_x + \left|\omega L_c\right|\left|I_{cxfq}\right| \qquad \omega = 2\pi f \tag{3}$$

From (3), it is clearly shown that V_{invxf} for APF must be larger than the load voltage V_x for reactive power compensation, no matter what the coupling inductor is. This also explains why the inverter part of the APF can only operate with a dc-link voltage higher than the peak of V_x value.

From Fig. 2(b), the inverter harmonic output voltage of the APF single-phase equivalent circuit model V_{invxn} at each n^{th} harmonic order can be expressed as:

$$V_{invxn} = \left|n\omega L_c\right|\left|I_{cxn}\right| \qquad n = 2,3\ldots\infty \tag{4}$$

where I_{cxn} is the n^{th} order harmonic compensating current. When the APF is performing compensation, the absolute reactive and n^{th} order harmonic compensating current should be equal to those of the loading, this yields:

$$\left|I_{cxfq}\right| = \left|I_{Lxfq}\right|, \quad \left|I_{cxn}\right| = \left|I_{Lxn}\right| \tag{5}$$

where I_{Lxfq} and I_{Lxn} are the reactive and n^{th} order harmonic current of the loading.

From (2) – (5), the inverter fundamental and each n^{th} harmonic order output voltages of the APF single-phase equivalent circuit model (V_{invxf}, V_{invxn}) can be calculated. Then the minimum dc-link voltage requirement (V_{dcx}) for the APF single-phase circuit model can be found by (1).

By using the generalized single-phase p-q theory [8], the reactive power and current harmonics in each phase can be compensated independently, thus the final required minimum dc-link voltage for the three-phase four-wire center-split APF will be the maximum one among the calculated minimum value of each phase (V_{dcx}), which is expressed in (6). Thus the deduced minimum dc-link voltage expression can work for both balanced and unbalanced loadings. Table I summarizes the minimum dc-link voltage deduction steps of the three-phase four-wire APF.

$$V_{dc} = \max(2V_{dca}, 2V_{dcb}, 2V_{dcc}) \qquad (6)$$

TABLE I. MINIMUM DC-LINK VOLTAGE DEDUCTION STEPS OF THE APF

1	Inverter fundamental output voltage: $V_{invxf} = V_x + \lvert \omega L_c \rvert \lvert I_{cxfq} \rvert$ Where $\lvert I_{cxfq} \rvert = \lvert I_{Lxfq} \rvert$, $\omega = 2\pi f$	(3) (5)
2	Inverter n^{th} harmonic order output voltage: $V_{invxn} = \lvert n\omega L_c \rvert \lvert I_{cxn} \rvert$ Where $\lvert I_{cxn} \rvert = \lvert I_{Lxn} \rvert$, $n = 2,3 \ldots \infty$, $\omega = 2\pi f$	(4) (5)
3	Minimum dc-link voltage: $V_{dc} = \max(2V_{dca}, 2V_{dcb}, 2V_{dcc})$ Where $V_{dcx} = \sqrt{\lvert V_{dcxf} \rvert^2 + \sum_{n=2}^{\infty} \lvert V_{dcxn} \rvert^2}$ $V_{dcxf} = \sqrt{2} V_{invxf}$, $V_{dcxn} = \sqrt{2} V_{invxn}$	(6) (1)

IV. SIMULATION VERIFICATION FOR THE APF MINIMUM DC-LINK VOLTAGE ANALYSIS

Fig. 3 shows the reactive and harmonic reference compensating current deduction and PWM control block diagram for the three-phase four-wire center-split APF, in which the three-phase v_x and i_{Lx} are necessary to determine the reference compensating currents i_{cx}^* by the single-phase p-q theory [8]. Initially, the phase instantaneous active power p_{Lx} and reactive power q_{Lx} are calculated by $p_{Lx} = v_{x\alpha}\ i_{Lx\alpha} + v_{x\beta}\ i_{Lx\beta}$ and $q_{Lx} = v_{x\alpha}\ i_{Lx\beta} - v_{x\beta}\ i_{Lx\alpha}$. To compensate the reactive power and current harmonics generated by the load, i_{cx}^* for each phase can be calculated by $i_{cx}^* = \frac{1}{A_x}\left[-v_{x\alpha} \cdot \tilde{p}_{Lx} + v_{x\beta} \cdot q_{Lx} \right]$, where $A_x = v_{x\alpha}^2 + v_{x\beta}^2$. The term $\tilde{p}_{Lx}$ can easily be extracted from p_{Lx} by using a low-pass filter (LPF) or high-pass filter (HPF). After the process of the instantaneous i_{cx}^* determination, the compensating current error Δi_{cx} together with hysteresis band H will be sent to the current PWM control part and the PWM trigger signals for the switching devices of the VSI can then be generated. And this control block diagram is applied for APF system in order to generate the required compensating current i_{cx}. In the following, since the load harmonic current contents beyond the 9th order are small, for simplicity, the required minimum dc-link voltage calculation will be taken into account up to 9th harmonic order only.

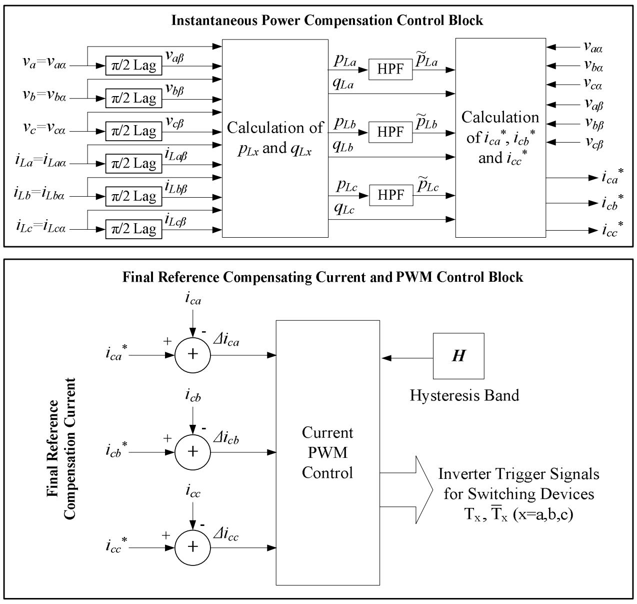


Figure 3. Control block diagram for the three-phase four-wire center-split APF

In order to verify the minimum dc-link voltage analysis in Section III, representative simulation results of the three-phase four-wire center-split APF system as shown in Fig. 1 will be given. The nonlinear loads are composed of three single-phase full bridge rectifiers, which act as harmonic producing loads. In order to simplify the verification in this paper, the dc-link is supported by external dc voltage source and the simulated three-phase loadings are approximately balanced. Table 2 lists the simulated system parameters for the APF and the current quality data of the loading. Simulation studies were carried out by using PSCAD/EMTD. From Table I, the required minimum dc-link voltage for the APF system can be calculated through (1) – (6), which is equal to V_{dc} =404.2V ($V_{dcu} = V_{dcL}$ = 202.1V).

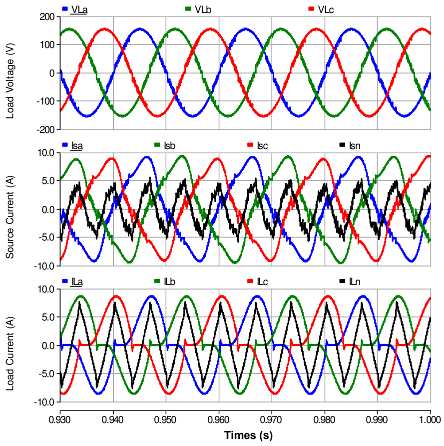
TABLE II. APF SYSTEM PARAMETERS FOR SIMULATIONS

System parameters		Physical values
System source-side	V_x	$110V_{rms}$
	L_s	1mH
	f	50Hz
APF	L_c	30mH
	C_{dc}	10mF
	V_{dcu}, V_{dcL}	180V, 200V, 220V
Nonlinear rectifier load	R_{Lx}	26Ω
	L_{Lx}	30mH
	C_{Lx}	200uF
Current quality data of Load	I_{Lx}	$5.3A_{rms}$
	DPF	0.835 (lagging)
	$\lvert I_{Lxfq} \rvert$	$2.79A_{rms}$
	$\lvert I_{Lx3} \rvert$	$1.35A_{rms}$
	$\lvert I_{Lx5} \rvert$	$0.35A_{rms}$
	$\lvert I_{Lx7} \rvert$	$0.14A_{rms}$
	$\lvert I_{Lx9} \rvert$	$0.07A_{rms}$

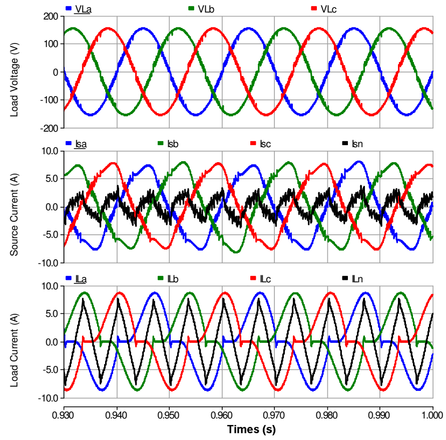
From Table III, before compensation, the system current and system neutral current are i_{sx} =5.30A$_{rms}$ and i_{sn} =4.09A$_{rms}$ respectively. The displacement power factor (DPF) is 0.835, the total harmonic distortion of system current ($THD_{i_{sx}}$) and load voltage (THD_{v_x}) are 30.0% and 1.82%, in which $THD_{i_{sx}}$ does not satisfy the international standards ($THD_{i_{sx}}$ <16% for IEC, $THD_{i_{sx}}$ <20% for IEEE) [9], [10].

Fig. 4 and Table III show the simulated compensation results of APF with different dc-link voltage levels. When the dc-link voltage $V_{dcu} = V_{dcL}$ = 180V (<202.1V), the APF is operating at rectifier mode, thus drawing active current by showing the increase of i_{sx} =6.00A$_{rms}$. After compensation, the compensated $THD_{i_{sx}}$ =18.4% and i_{sn} is 2.93A$_{rms}$, in which the compensated $THD_{i_{sx}}$ does not satisfy the international standards [9], [10]. When the dc-link voltage increases to $V_{dcu} = V_{dcL}$ = 200V, since this value is closer to the required 202.1V, the APF can obtain better compensating performances with i_{sx} =5.15A$_{rms}$, $THD_{i_{sx}}$ =12.5% and i_{sn} = 1.60A$_{rms}$, in which the compensated $THD_{i_{sx}}$ satisfies the international standards [9], [10]. However, the APF is still operating at rectifier mode due to insufficient dc-link voltage level. When the dc-link voltage increases to $V_{dcu} = V_{dcL}$ = 220V, which is higher than the minimum 202.1V requirement, the APF can operate at both inverter and rectifier modes and achieve the best compensation performances with i_{sx} reduces to 4.30A$_{rms}$, $THD_{i_{sx}}$ =7.6% and i_{sn} = 0.45A$_{rms}$ among the three cases. Moreover, the compensation results as shown in Table III satisfy the international standards [9] – [10]. From Table III, the three cases can compensate the DPF from 0.835 to 0.995 or above. Moreover, the compensated THD_{v_x} satisfies the international standard [11].

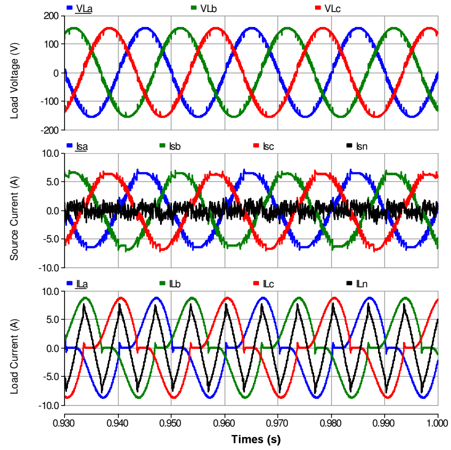
Fig. 4 and Table III verified the APF minimum dc-link voltage deduction. With different system voltage level, coupling inductor value and loading current contents, the APF requires different minimum dc-link voltage value for operation.



(a) V_{dcu}, V_{dcL}=180V



(b) V_{dcu}, V_{dcL} =200V



(c) V_{dcu}, V_{dcL} =220V

Figure 4. APF simulation results: (a) V_{dcu}, V_{dcL} =180V, (b) V_{dcu}, V_{dcL} =200V, (c) V_{dcu}, V_{dcL} =220V

TABLE III. SIMULATED RESULTS BEFORE AND AFTER APF COMPENSATION AT DIFFERENT V_{DCU}, V_{DCL} LEVELS

Simulation results	V_{dcu}, V_{dcL} (V)	i_{sx} (A$_{rms}$)	DPF	THD_{isx} (%)	THD_{vx} (%)	i_{sn} (A$_{rms}$)
Without Comp.	---	5.30	0.835	30.0	1.82	4.09
APF	180	6.00	0.996	18.4	2.28	2.93
	200	5.15	1.000	12.5	2.30	1.60
	220	4.30	1.000	7.6	2.54	0.45

V. CONCLUSION

This paper aims to investigate the minimum dc-link voltage design for three-phase four-wire center-split active power filters (APF). Firstly, its single-phase equivalent circuit models are built and proposed. Based on the circuit models and current quality data of the loading, the minimum dc-link voltage expression for the three-phase four-wire APF is deduced and discussed, which can work for both balanced and unbalanced loadings. Finally, simulation results of the three-phase four-wire center-split APF are presented to verify the deduced minimum dc-link voltage expression.

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