Capacitor Current Feedback Active Damping for Shunt Active Power Filter with Output LLCL Filter

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***Abstract*—A high-order LLCL has excellent attenuation performance of ripple harmonics generated by VSI. The LLCL filter is especially effective at switching frequency to mitigate the switching ripple harmonics. However, like the other high-order filters, LLCL filter has resonance problem, which must be damped to have stable system. In literature, passive damping and active damping methods are proposed for grid-connected VSI. However, the active damping techniques have not been considered for SAPF with LLCL filter yet. Thus, in this paper, LLCL filter for Shunt Active Power Filter with Active Damping method is proposed and analyzed to suppress the resonance of LLCL filter and stabilize the control of SAPF.**

Keywords—SAPF, LLCL Filter, Resonance, Active Damping, Switching Ripple Harmonics

I. INTRODUCTION

Due to growing penetration of power electronics based loads and various other non-linear loads into electric system, the distortion of current and voltage waveforms has adverse impact on other significant loads and degrade the power quality in the distribution system [1, 2]. Thus, to keep power quality of the distribution system under limits of standards determined in [3] and [4] and to prevent the critical loads from the distortion, a number of custom power devices (CPD) have been suggested and improved by the researchers [5]. Shunt Active Power Filter (SAPF) is a CPD connected in parallel with the non-linear loads in order to eliminate current harmonics emerged from the non-linear loads [6-8]. Despite various SAPF topologies, three-phase four-wire SAPF is more attractive for distribution system since it has compensation capability of zero sequence components as well [9, 10].

Voltage source inverters (VSI), main part of SAPF, have been commonly used while elimination of distorted current components. Sinusoidal pulse width modulation (SPWM) technique is widely applied in SAPF to control switching signal of VSI. However, the compensation currents generated by VSI include high-order ripple harmonics at switching frequency and its multiples. Conventionally, single L filter or LC filter was exploited at the end of VSI to filter switching ripple harmonics (SRH) and to perform interfacing with the grid [6, 11]. In recent years, the use of LCL filter and LLCL filter with VSI have been proliferation instead of single L filter and LC filter owing to better SRH attenuation and use of lower inductance benefits [12, 13]. In comparison to LCL filter, LLCL filter has more profound mitigation of SRH at switching frequency thanks to nearly zero impedance of shunt L-C branch at switching frequency [13, 14]. However, similar to LCL filter, LLCL filter has resonance issue that get the system unstable if it is not dampened.

Passive damping (PD) or active damping (AD) is applied to damp the resonance for grid-connected VSI in literature [15]. In [12] and [16], simple resistor PD method is used for SAPF with LLCL filter, and the performance of damping is assed for different resistor values. However, PD method reduces the overall efficiency of the system because of damping resistor losses. In contrast, there is no damping power losses once AD method is used. Even so, AD methods have not been studied yet for SAPF with LLCL filter. Thus, this paper aims to first examine AD method for three-phase four-wire SAPF with LLCL filter. To fulfill AD, the current flowing on shunt L-C branch is fed back. The entire control structure with proposed AD method is provided. The frequency characteristic is evaluated and compared with PD method. In order to investigate and verify the performance of AD on SAPF with LLCL filter a model is developed and constructed in Matlab/Simulink environment.

II. MODELLING OF SAPF WITH LLCL FILTER

In this section, the configuration of the proposed SAPF with LLCL filter and AD method based control scheme are presented. Fig.1 demonstrates the circuit diagram of three-phase four-wire grid-connected SAPF and the proposed AD method control structure. The circuit diagram consists of three-phase VSI bridge with capacitor midpoint connected to neutral wire, LLCL filter and non-linear loads, as shown in Fig. 1a.

A. Model of LLCL Filter

The single-phase equivalent circuit schematic of LLCL filter is shown in Fig. 2a, where L_1, L_2, L_f and C_f are inverter-side inductance, grid-side inductance, shunt branch inductance and shunt branch capacitance, respectively. R_1 and R_2 are series resistances and assumed zero for the filter analysis. V_i and V_g refer to inverter output voltage and grid voltage at point of common coupling (PCC). I_{if}, I_{gf} and I_{cf} are inverter-side grid-side and shunt branch currents, respectively.

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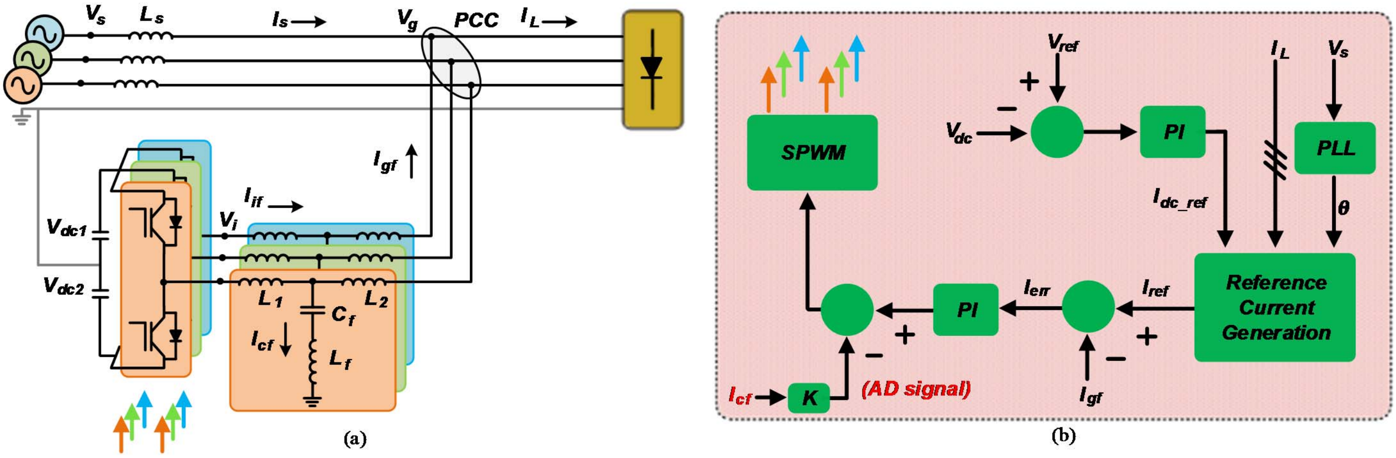

Fig. 1. The block diagram of 3P4W SAPF (a) Power circuit and (b) Control structure

The block diagram of LLCL is illustrated in Fig. 2b. Since grid-side current is controlled in this study, the transfer function of the grid-side current to inverter voltage can be derived as,

$$G_{V_i \to I_{gf}}(s) = \frac{L_f C_f s^2 + 1}{(L_1 L_2 C_f + L_T L_f C_f)s^3 + L_T)s} \quad (1)$$

$$\omega_r = \sqrt{\frac{L_T}{L_1 L_2 C_f + L_T L_f C_f}} \quad (2)$$

Where, ω_r is the angular resonance frequency and $L_T = L_1 + L_2$.

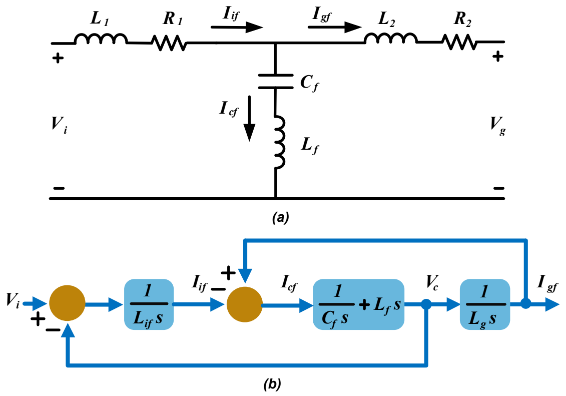

Fig. 2. Single-phase equivalent circuit of LLCL filter (a) Circuit schematic and (b) Block diagram

To design the parameters of LLCL filter for SAPF, the limitations for each parameter and design rule are defined in [12]. Thus, it is not mentioned here due to out of the scope of this study.

According to the transfer function (1), the frequency behaviors of single L filter, LCL filter and LLCL filter are shown Fig. 3. It is shown that both LCL filter and LLCL filter have superior SRH attenuation than L filter in the frequencies higher than resonance frequency. LLCL filter has effective mitigation at switching frequency which is almost -200 dB, where LCL filter magnitude is -50 dB. However, at the higher frequencies than switching frequency, LCL filter is better compared with LLCL filter. In the frequency range lower than resonance frequency, LCL filter and LLCL filter have almost similar frequency response.

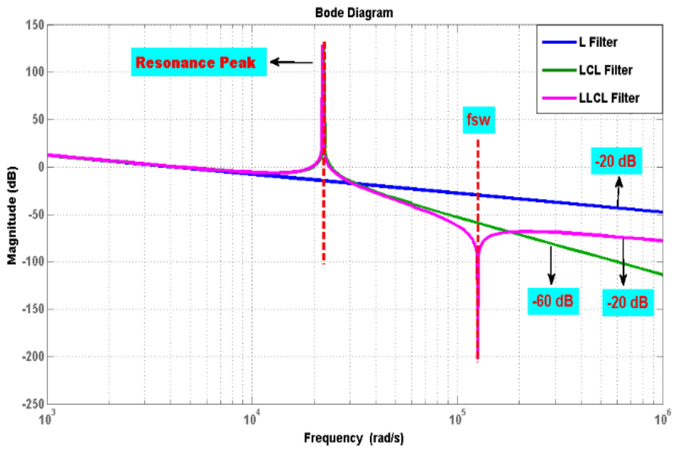

Fig. 3. Frequency responses of single L, LCL and LLCL filters

The resonance peak of LLCL filter is suppressed by either PD or AD. In this study, AD method is applied to damp the resonance and stabilize the system. The control of entire system and AD method is given below in detail.

B. Control Scheme with AD

The control structure of SAPF includes DC link control, phase-locked loop (PLL), reference current generation, current control and AD, as illustrated in Fig. 1b. The reference current signal is generated by d-q frame, and PI controllers are used to regulate DC link voltage and reference currents.

The block diagram of SAPF controller with AD of LLCL filter is demonstrated in Fig. 4. The AD signal is obtained through measuring the current of $L_f - C_f$ branch and multiplying with a feedback function $K(s)$. $K(s)$ can be easily chosen as constant.

The bode plots of open-loop transfer functions of LLCL

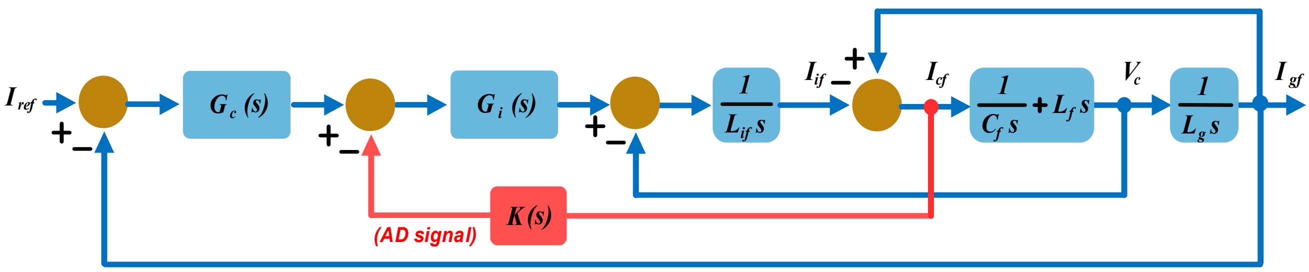

Fig. 4. Block diagram of SAPF controller with actively damped LLCL filter

filter with no damping, simple resistor PD and shunt branch current feedback AD are shown in Fig. 5. It can be seen that the system is unstable in the case of no damping. The system becomes stable if PD or AD is used. However, although the system is stable with PD method, the attenuation superiority of LLCL filter at switching frequency is weakened. On the contrary, when AD method is applied with the controller, the mitigation performance is improved while providing adequate resonance damping.

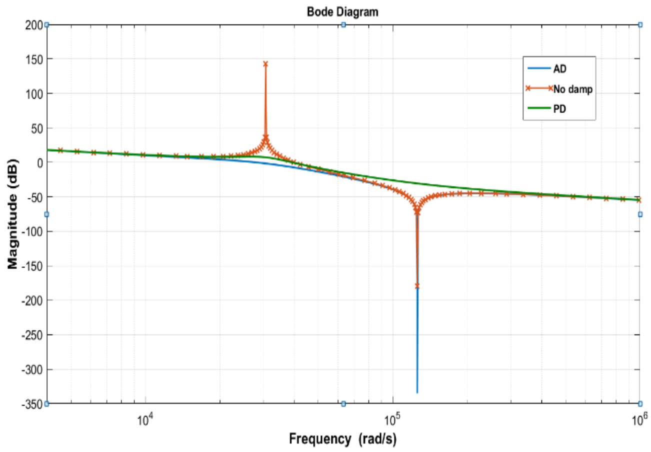

Fig. 5. Open-loop bode plots of SAPF controller with LLCL filter once no damping, PD and AD

III. Performance Results

In order to verify the proposed system, a simulation model of 80 kVA 3P-4W SAPF with output LLCL filter is constructed in Matlab/Simulink. The parameter values of SAPF, supply and non-linear loads are shown in Table 1. The non-linear loads involve both 3-ϕ uncontrollable rectifier and 1-ϕ uncontrollable rectifiers, zero-sequence harmonics flow on neutral line.

Table 1. System Parameters

Symbol	Meaning	Value
Vs	Supply Phase-Phase Voltage	380 V
Sapf	Nominal Power of APF	80 kVA
f1	Grid fundamental frequency	50 Hz
fsw	Modulation frequency of APF	20 kHz
Vdc1=Vdc2	DC link voltage of APF	375 V
L1	Grid-side inductance	200 µH
L_2	Converter-side inductance	40 µH
L_f	LC branch inductance	1.05 µF
Cf	LC branch capacitance	60 µH

Figure 6 demonstrates the waveforms of grid voltage, load currents, inverter-side currents, grid-side currents and source currents. The THD of load current is 23%. Whereas, after the compensation with SAPF, the THD of source current is reduced to 1.96% which satisfies IEEE-519 Std. 1993.

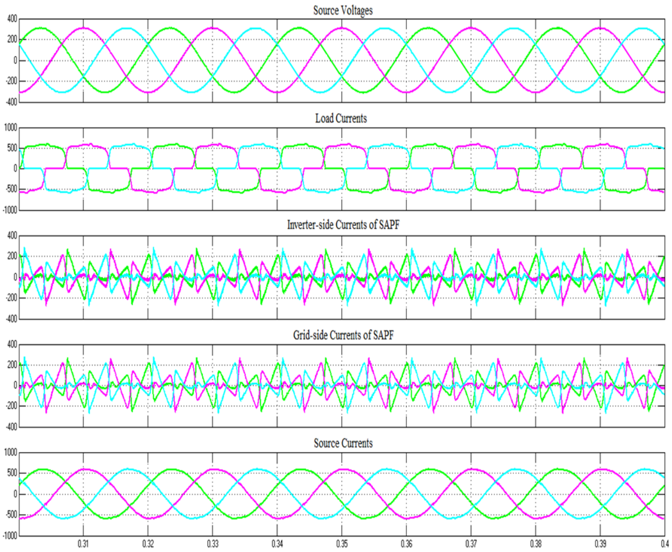

Fig. 6. The waveforms of the Proposed AD for SAPF with LLCL filter

The waveform and FFT window are shown in Fig. 7. It can be seen that SRH components around the switching frequency are well attenuated. Besides, the neutral currents of load, SAPF and source are shown in Fig. 8. As seen, the current flow on source neutral wire is almost eliminated.

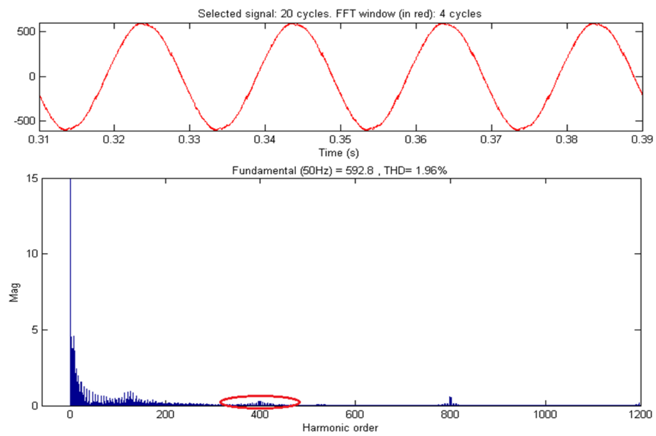

Fig. 7. The waveform and FFT window of source current

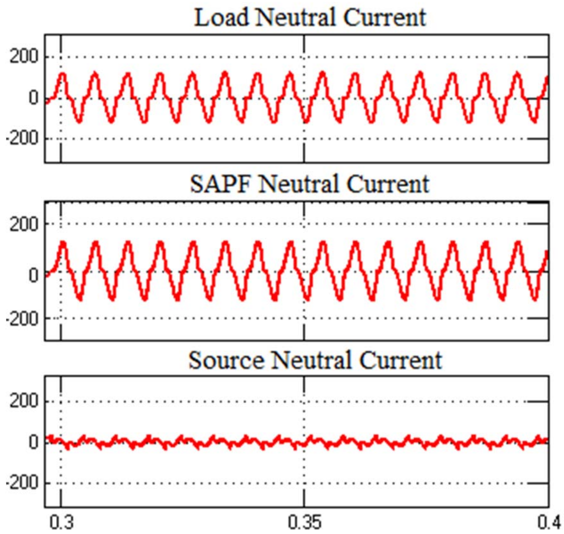

Fig. 8. Neutral currents of load, SAPF and source

IV. Conclusions

In this paper, an AD based on shunt branch current feedback of LLCL filter for three-phase four-wire SAPF has been first carried out and assessed. The transfer function of LLCL filter is given, and frequency response illustrated and compared with single L filter and LCL filter. Besides, open-loop bode-plot of actively damped LLCL filter for SAPF is provided, then, a comparison with no damping and PD cases is performed. In order to demonstrate the proposed LLCL with AD for SAPF system, a simulation model is constructed in Matlab Simulink. As a result, the analysis and simulation results show that LLCL filter with AD has good ripple suppression at the switching frequency and low THD value. However, its performance in the frequency range of higher than switching frequency is a little poor.

Acknowledgment

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