Modelling of Output Admittance Coupling Between Shunt Active Power Filters and Non-linear Loads

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***Abstract*— Nowadays Shunt Active Power Filter (SAPF) system still suffers from stability issue which heavily detect its performance. In this paper, an improved system level model is proposed to investigate the coupling effect that will cause the system level instability. This model describes the coupling effect with an additional output admittance and shows system stability more directly. In order to investigate the correctness of the proposed method, a grid including the SAPF and a non-linear load is modelled with both conventional approach and proposed modeling method. Simulations are carried out with the same parameters. Results show that the instability of the grid current observed in the simulation results is not reflected in the stability analysis based on the conventional model. On the other hand, the stability analysis with the new model matches the simulation results very well. Also, further verification is made by a frequency-sweep result, which proves the accuracy of proposed model.**

Keywords—SAPF, system stability, modelling, output admittance coupling

I. INTRODUCTION

Under the dual pressure of energy demand and environmental protection, power electronic converters, which shows superiority in both flexibility and efficiency, is experiencing a rapid growth[1]. Many renewable generation and energy storage technologies are DC, and were connected to the utility grid via DC/AC and AC/DC converters. On the other hand, there are high penetration of DC loads in power grid like adjustable speed drives, power supplies, etc[2]. These DC loads have a front-end rectifier to convert AC grid voltage to DC voltage. DC microgrid technology was proposed in recent years, which has the advantages of effective integration those DC power sources and loads, and AC/DC converters were introduced as the interface to the AC grid. The AC/DC converters, especially the passive rectifiers, due to their non-linear behavior, cause power quality (PQ) issues, e.g. harmonic currents. The harmonic currents cause voltage disturbances, decrease in overall efficiency and damage of key devices. Also, it adversely affects the performance of relays, circuit breakers, protecting equipment and other sensitive devices in power system.

Due to the strict utility harmonic standards, the harmonic problems brought by the non-linear load must be coped properly. To deal with it, passive power filters (PPF), which are designed to offer low-impedance or high-impedance branches for reducing or blocking harmonic currents, are widely used in demand-side and distribution system[3]. However, the passive power filters also have significant drawbacks such as heavy weight, non-flexibility in harmonic reduction, etc. In contrast, the shunt active power filter (SAPF) has been proved to be a superior solution for decades[4], [5], , due to better dynamic characteristic for fast-change loads and selective compensation ability. Since SAPF is used for compensating load harmonic current, it is common to simplify the load to a harmonic current source in the modelling of SAPF[6], [7]. In general, SAPF is thought to be in favor of system stability by eliminating harmonic currents and stability issues are rarely taken into consideration. However, it is found that stability analysis with that model does not match with the simulation results in some cases, especially when its output admittance is considerable.

In this paper, a more accurate model of SAPF is proposed, where the load output impedance is also taken into consideration. The rest of this paper is organized as follows: in Section II, stability analysis based on conventional model of SAPF is done and simulation results are obtained to show the mismatch, an improved model and stability analysis based on the new model are indicated in Section III, the validation of proposed impedance model is carried out through a frequency-sweep result in Section IV, the paper is concluded and future work is discussed in Section V.

II. CONVENTIONAL SAPF MODEL AND STABILITY ANALYSIS

Fig. 1 shows the diagram of a three-phase power system. In this figure, utility grid is simplified to a voltage source in series with the system impedance represented by L_g in series with R_g, meanwhile non-linear load and SAPF are connected to the grid in parallel. The SAPF with an LCL filter usually uses grid current control strategy to compensate harmonics, which extracts reference current from load current directly and produces current with equal amplitude but in opposite phase.

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As shown in this figure, L_{f2} is grid side filter inductor, L_{f1} is converter side filter inductor and C_f is filter capacitor.

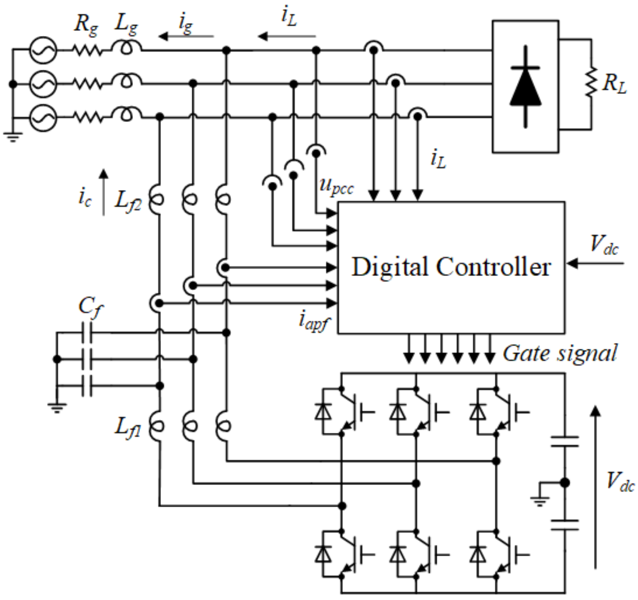


Fig. 1. A shunt active power filter together with non-linear load and grid.

Non-linear load, supposed to be in series with output filter, is generally simplified to a harmonic current source and therefore the reference current is regarded as a given value when designing the current control loop of SAPF. Thus, the control diagram of the SAPF is the same as that of conventional inverter[8] and is illustrated in Fig. 2(a). The control of dc voltage, which is generally designed to be a slow control loop, is not discussed in this paper, and will not affect the fast current control loop with a proper control bandwidth. Also, the influence of phase lock loop is not included for simplification. In this figure, $G_c(s)$, $G_d(s)$ represent the compensator and delay caused by digital controller and the PWM converter, respectively. The SAPF current then can be derived and it is shown in Eqn. (1), where the close-loop gain $G_{cA}(s)$and the output admittance $Y_{oA}(s)$of the SAPF are obtained as Eqn. (2) and (3).

$$I_{\mathrm{apf}}(s) = G_{cA}(s)I_{ref}(s) - Y_{oA}(s)V_{pcc} \quad (1)$$

$$G_{cA}(s) = \frac{G_c(s)G_d(s)Z_{Cf}/(Z_{L1}Z_{L2}+Z_{L1}Z_{Cf}+Z_{L2}Z_{Cf})}{1+G_c(s)G_d(s)Z_{Cf}/(Z_{L1}Z_{L2}+Z_{L1}Z_{Cf}+Z_{L2}Z_{Cf})} \quad (2)$$

$$Y_{oA}(s) = \frac{(Z_{Cf}+Z_{L1})/(Z_{L1}Z_{L2}+Z_{L1}Z_{Cf}+Z_{L2}Z_{Cf})}{1+G_c(s)G_d(s)Z_{Cf}/(Z_{L1}Z_{L2}+Z_{L1}Z_{Cf}+Z_{L2}Z_{Cf})} \quad (3)$$

Fig. 2 (b) shows the equivalent circuit used to analyse system stability. In this figure, Norton equivalent model is applied to both non-linear load and SAPF, meanwhile Thevenin equivalent model is used for the utility grid. The grid current can then be elaborated as Eqn. (4), where $G_1(s)$, $G_2(s)$, and $Y_1(s)$ are defined as Eqn. (5)~(7), respectively. It can be seen that the stability is actually determined by the impedance ratio $T(s)$ in Eqn. (8).

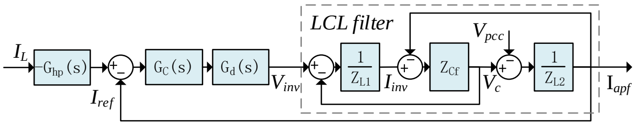
$$I_g(s) = G_1(s)I_{Ls}(s) + G_2(s)G_{cA}(s)I_{ref}(s) - Y_1(s)V_g \quad (4)$$

$$G_1(s) = \frac{I_g(s)}{I_{Ls}(s)}\Big|_{I_{ref}=0,V_g=0} = \frac{1}{1+Z_g(s)[Y_{oA}(s)+Y_{oL}(s)]} \quad (5)$$

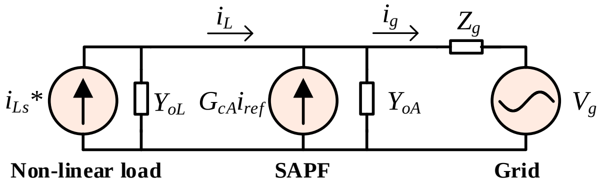
$$G_2(s) = \frac{I_g(s)}{G_{cA}(s)I_{ref}(s)}\Big|_{I_{Ls}=0,V_g=0} = \frac{1}{1+Z_g(s)[Y_{oA}(s)+Y_{oL}(s)]} \quad (6)$$

$$Y_1(s) = \frac{I_g(s)}{V_g(s)}\Big|_{I_{Ls}=0,I_{ref}=0} = -\frac{Y_{oA}(s)+Y_{oL}(s)}{1+Z_g(s)[Y_{oA}(s)+Y_{oL}(s)]} \quad (7)$$

$$T(s) = Z_g(s)[Y_{oA}(s) + Y_{oL}(s)] \quad (8)$$



(a) A typical control diagram of a SAPF



(b) equivalent circuit of the system in Fig. 1.

Fig. 2. Control diagram of a SAPF and the equivalent circuit

TABLE I. PARAMETERS OF SAPF AND NON-LINEAR LOAD

Symbol	Meaning	Value
	Circuit Parameters	
V_s	Grid voltage	380V
f_g	Grid frequency	50Hz
L_g	Grid inductor	1mH
R_g	Grid impedance	0.1ohm
V_{dc}	DC-link voltage	800V
L_1	Converter side filter inductor	1.94mH
L_2	Grid side filter inductor	1mH
C_f	Filter Capacitor	4.7uF
C_L	Load Capacitor	470uF
R_L	Load Resistance	0.1ohm
	Quasi-PR Control parameters	
f_s	Switching frequency	10kHz
K_p	Proportional gain	7
K_r	Integral gain	200
Q	Quality factor	600
ω_r	Resonance frequency(N=2,5,7)	2*pi*N*f_s

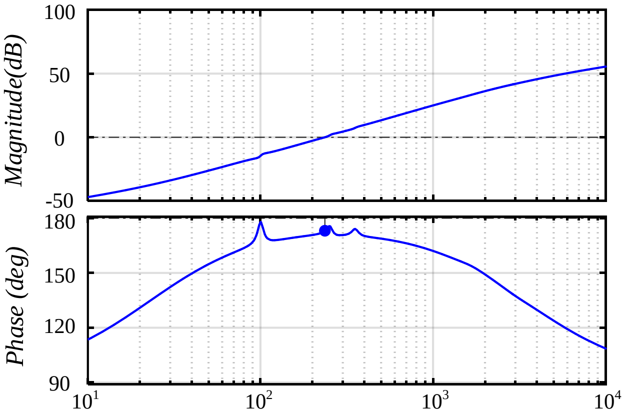


Fig. 3. Bode plot of T(s) with the conventional model

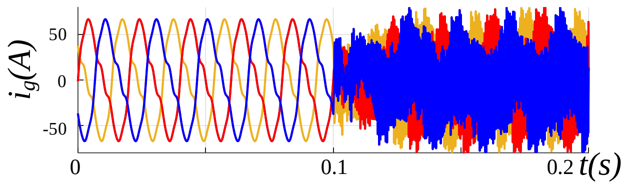
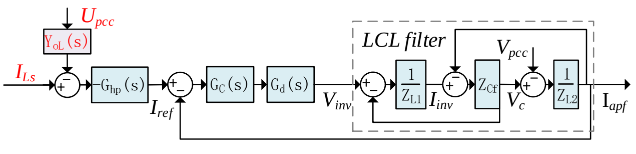


Fig. 4. Simulated grid current with parameters listed in TABLE I

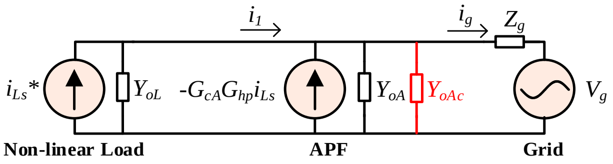
The parameters of SAPF and non-linear load are listed in Table I. As seen, the SAPF compensates 2nd, 5th and 7th harmonic currents by using a typical Quasi-PR controller. And the non-linear load is simplified as a harmonic current source in parallel with RC load. The bode plot of open circuit gain $T(s)$ is shown in Fig. 3. It can be seen that there is no -180° crossing when its magnitude is larger than 0dB, which means the system is stable in light of nyquist stability criterion. Actually, these parameters of SAPF are well designed based on the conventional model and promise a passive output admittance, which guarantees the stability of this grid connected system. However, a simulation result of grid current waveform with these parameters is given in Fig. 4, which shows unexpected results. In this simulation, the non-linear load is connected to electric grid at the beginning and running at a stead state. At 0.1s, the SAPF is plugged in and then system becomes unstable, which indicates the defect of the conventional model.

III. MODIFIED SAPF MODEL AND STABILITY ANALYSIS

The analysis in section II shows the inaccuracy of conventional model. In fact, the reference current of SAPF extracted from load current is not constant, and it is influenced by both the voltage at PCC point (V_{pcc}) and the output current of non-linear load. However, conventional model only takes the latter into consideration and neglects the former. Then by considering $V_{pcc,}$ a modified control diagram is shown in Fig. 5(a), in which the current control loop is the same as that in the traditional model but the current reference is different. Normally, reference current generation of SAPF is by using a high pass filter $-G_{hp}(s)$to extract the harmonics in the load current I_L, as shown in Eqn. (9). Hence, substituting this equation into Eqn. (1), SAPF current can be written as Eqn. (10). Comparing to conventional one, it can be seen that SAPF output admittance Y_{oAm}(s) has an additional item Y_{oAc}(s) as shown in Eqn. (11). This additional admittance associates with both load's output admittance and close control loop gain.



(a) modified current control diagram of SAPF



(b) modified equivalent circuit of the system in Fig. 1

Fig. 5. Modified control diagram and the equivalent circuit

$$I_{ref} = -G_{hp}(s)I_L = -G_{hp}(s)(I_{Ls} - Y_{oL}(s)V_{pcc}) \quad (9)$$

$$I_{apf}(s) = -G_{hp}(s)G_{cA}(s)I_{Ls} - (Y_{oA} + Y_{oAc})V_{pcc} \quad (10)$$

$$\begin{aligned} Y_{oAm}(s) &= Y_{oA}(s) + Y_{oAc}(s) \\ &= Y_{oA}(s) - G_{hp}(s)G_{cA}(s)Y_{oL}(s) \quad (11) \end{aligned}$$

According to these equations above, the equivalent circuit can be modified to Fig. 5(b). Moreover, the characteristic of additional admittance $Y_{oAc}(s)$ is illustrated in Fig. 6. As seen, negative resistance will occur at some frequency region, where the phase angle is beyond -90° ~ 90°, and it is highlighted with shadow. Because of this, the system might become unstable.

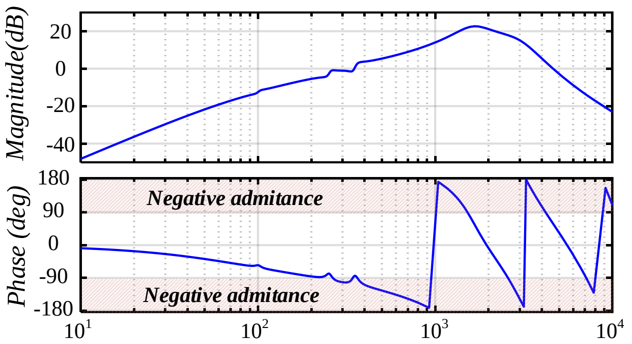
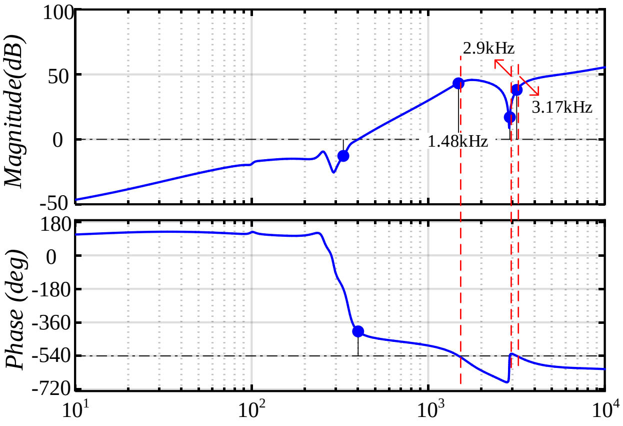


Fig. 6. Additional part of SAPF output admittance

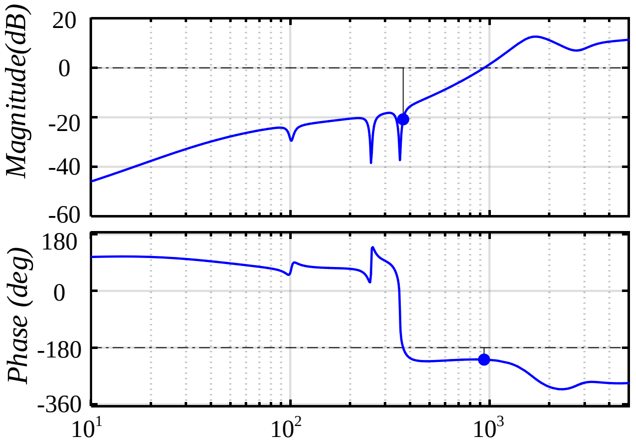
From the modified equivalent circuit, a new open-loop gain of the interconnected system $T_m(s)$ is deduced to analyze system stability, which is shown in Eqn. (12).

$$T_m(s) = Z_g(s)(Y_{oAm}(s) + Y_{oL}(s)) \quad (12)$$

Bode diagram of $T_m(s)$ is then plotted and it is shown in Fig. 7(a). At the frequency of 1.48kHz, 2.9kHz and 3.17kHz, the phase is -180° meanwhile its magnitude is larger than 0dB. Thus the system is unstable, which matches with the simulation results in section II. If the load resistance changes from 0.1 ohm to 10ohm, this system will be stable according to its bode plot in Fig. 7(b). Simulation with the same parameters has been done and result is shown in Fig. 8. SAPF is plugged in at 0.1s and this grid connected system is unstable. After that, the output admittance of non-load changes at 0.2s and the system become stable again. This is in consistent with the analysis done by modified model.



(a)R_L=0.1ohm



(b)R_L=10ohm

Fig. 7. Bode plot of Tm(s) with the modified model

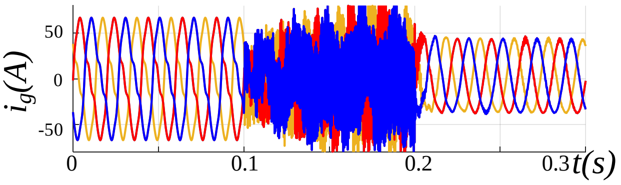


Fig. 8. Simulated grid current with load change

IV. IMPEDANCE MODEL VALIDATION

To verify the accuracy of proposed model, a frequency-sweep result of output admittance is carried out in Simulink. Due to the coupling of non-linear load and SAPF, these two are considered as a whole. A fixed voltage valued 220V(phase to phase RMS voltage) with 50Hz is applied as grid voltage to set up an operation point. Then, the total output admittance of SAPF and non-linear load can be obtained through the response of grid current to an input grid voltage of the same frequency which is much smaller than 220V, while equivalent harmonic current source $I_{Ls}(s)$ and grid impedance $Z_g(s)$ are set to zero. Therefore, the simulation model for frequency-sweep analysis is demonstrated in Fig. 9.

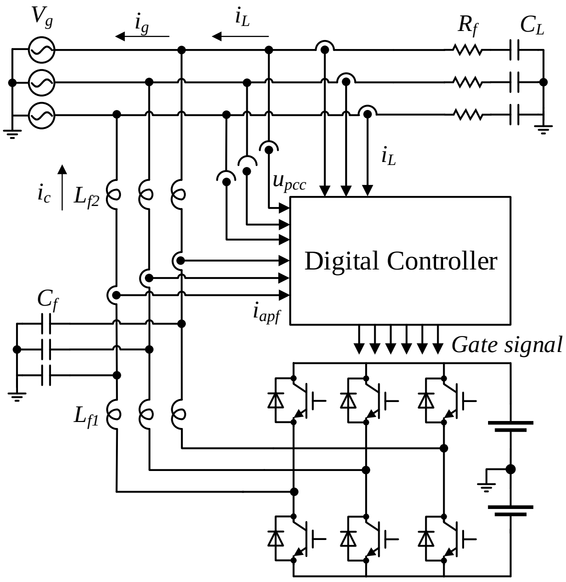


Fig. 9. Simulation Model for frequency-sweep analysis

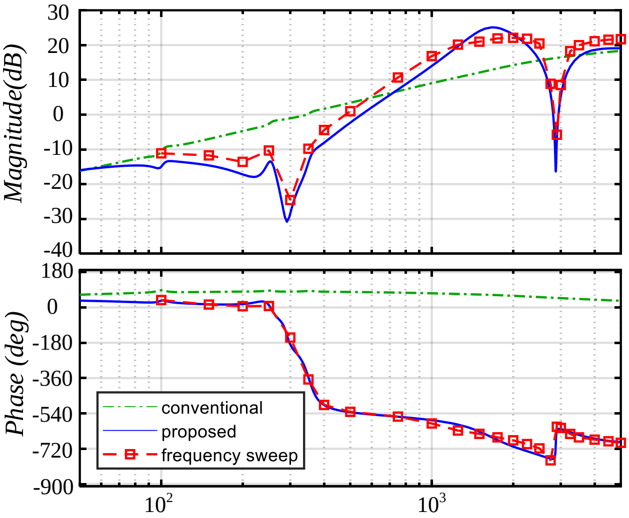


Fig. 10. Output admittance of SAPF and non-linear load

Fig. 10 shows the comparison of total output admittance among conventional model, proposed model and frequency-sweep result. In this figure, it can be seen that the conventional model turns out to be quite different from the others, while the proposed impedance model matches with the frequency-sweep result of simulation model very well at all frequency.

V. CONCLUSION

SAPF is meant to compensate the harmonic current injected into the grid. But in this paper, it is found that plug-in of a SAPF lead to instability of grid current when the grid impedance is considerable. However, this instability cannot be reflected with a conventional SAPF model, and thus the model cannot be used for a proper controller design of SAPF especially when the grid impedance is not negligible. In order to solve this issue, an improved model of SAPF is proposed in this paper. The coupling between the output admittance of the non-linear load and SAPF is taken into account in the improved model. The stability analysis with the new model matches the simulation results very well in terms of unstable region and the frequency-sweep result of output admittance matches with the improved model as well, which prove the effectiveness of the new model. For the future work, a prototype is being established for verification.

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