Series Active Filter Control with A Novel Load Voltage Harmonic Extraction Method

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Abstract – **Series Active Filters (SAF) are designed for harmonic isolation and load voltage regulation of single-phase and three-phase voltage harmonic source type nonlinear loads. The novel Absolute Value Method (AVM) for load voltage harmonic extraction is proposed and applied in the control algorithm of SAF. Harmonic isolation and load voltage regulation performances of 2.5 kW single-phase and 10 kW three-phase SAF compensated systems are evaluated by detailed simulations. Via simulations it is shown that AVM yields superior harmonic isolation and load voltage regulation performance compared to the conventional low/high pass filtering method. Theory, and simulations are well correlated and illustrate the feasibility of the proposed method.**

Keywords – **Series Active Filter, Harmonic Extraction, Absolute Value Method, Voltage Harmonics, Voltage Sag.**

I. INTRODUCTION

The electric power quality in a power system is determined by the quality of the voltage waveform supplied by the utility and the quality of the current waveform drawn by the load. Power quality problems are defined as problems manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment. These problems can be classified into two groups considering sources of problems: utility and load related problems. Utility related problems are mainly interruption, voltage sag (undervoltage), voltage swell (overvoltage), voltage unbalance (imbalance), and voltage fluctuation (flicker). Load related problems are load harmonic current and excess of reactive current [1], [2], [3].

The first group includes active filters, which are designed to mitigate harmonic problems. These are the well known Series Active Filter (SAF), Parallel Active Filter (PAF), and hybrid active filters [4], [5], [6]. The second group includes power electronics circuits, which are designed to correct the utility voltage variations and they are devices such as thyristor tap changer based voltage regulator, UPS, and Dynamic Voltage Restorer (DVR) [3], [7], [8].

Since SAF and DVR have the same circuit topology, SAF can be used as both harmonic mitigator and voltage corrector by adding a fundamental voltage control algorithm to SAF. Thus, SAF can provide a solution for both the utility and load related power quality problems and has more functionalities than PAF and DVR [9], [10], [11].

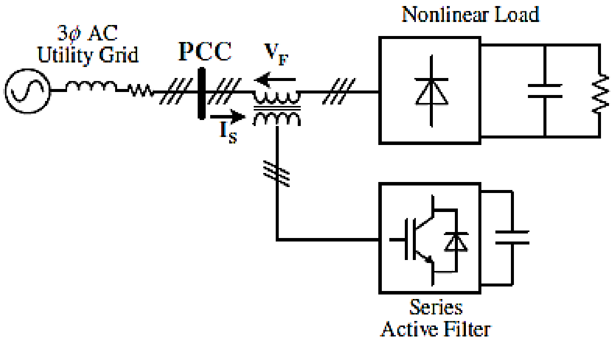

Fig.1. The series active filter basic connection diagram.

II. SERIES ACTIVE FILTER

SAF isolates the harmonic voltages of a nonlinear load and utility from each other such that harmonic current flow is prohibited and it regulates the load voltage against the voltage variations of the utility. Shown in Fig. 2, the circuit topology and control of the SAF are described briefly as follows.

Although the power circuit of SAF depends on whether it is designed for single-phase or three-phase loads, the main circuit blocks remain the same for either case. The main circuit blocks are Voltage Source Inverter (VSI), Switching Ripple Filter (SRF), and Series Injection Transformer (SIT), as shown in Fig. 2 , in the single-phase configuration.

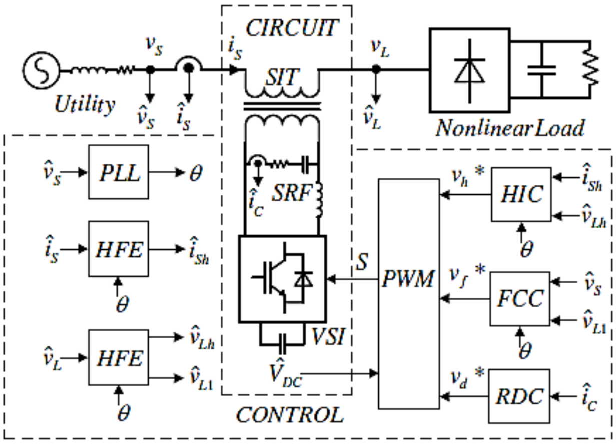

Fig.2. The power circuit and the control system of SAF .

The SAF control system consists of six main units. Shown in Fig.2, these are Harmonic Isolation Controller (HIC), Fundamental Component Controller (FCC), Resonance Damping Controller (RDC), Pulse Width Modulator (PWM), Phase Locked Loop (PLL), and Harmonic/Fundamental Extractor (HFE).

III. HARMONIC ISOLATION

The voltage harmonic isolation by SAF is based on two control principles. The first principle is that SAF emulates a virtual resistor (Khi) for the line harmonic current (i_{Sh}) . This requires the measurement of the line current and the decomposition of its harmonic component. The second principle is that SAF applies the load harmonic voltage (v_{Lh}) with opposite sign to the measured and decomposed load harmonic voltage value. The total control rule for the harmonic isolation is given in (1). Applying this reference voltage ($v_{SAFh}{}^{*}$) between the utility and the load in series, the equivalent circuit for the harmonic quantities is analyzed in frequency domain.

$$V^{*}_{SAFh} = K_{hi} . \hat{i}_{Sh} - K_{hv} . \hat{v}_{Lh} \tag{1}$$

IV. LOAD VOLTAGE REGULATION

The load voltage regulation involves the control of the fundamental component of load voltage. In order to regulate the load fundamental voltage (v_{L1}), a feedback controller ($G_c(s)$) can be utilized to reject disturbances originating from the load and/or the utility. Moreover, in order to reject the line voltage disturbances, a feedforward controller for the line fundamental frequency voltage (v_{S1}) can be used. Using these controllers, the reference voltage generated for the load voltage regulation in s-domain ($v_{SAFf}{}^{*}(s)$) is given in (2).

$$V^{*}_{SAFf}(s) = G_C(s)\left(\hat{V}_{L1}(s) - V^{*}_{L1}\right) + \left(\hat{V}_{S1}(s) - V^{*}_{S1}\right) \tag{2}$$

After generating the reference voltage for the harmonic isolation and the load voltage regulation, the power circuit of the SAF system realizes this reference voltage such that the power conditioning is achieved.

VI. HARMONIC/FUNDAMENTAL EXTRACTOR

There are different approaches for harmonic and fundamental frequency signal extraction. In this study, the most popular method based on the 'de – qe' frame in the literature, which is called Conventional Method (CM) in this thesis and the application-specific novel method called Absolute Value Method (AVM) developed to decompose the harmonic and fundamental components of the load voltage for the SAF applications with the single-phase and the three-phase diode rectifier loads with a DC bus capacitor and a resistor are considered.

A. CM MODE

In CM, signal decomposition is realized in 'de-qe' frame such that the transformations from the measured single-phase and three-phase signals to two-phase signals are performed. These two signals are composed of a DC and an AC components, which represents the fundamental frequency and the harmonic frequency components as given in (3). By means of low and/or high pass filters (LPF/HPF), these DC and AC components can be separated as shown in (4) [12] .

$$\begin{bmatrix} x_{de} \\ x_{qe} \end{bmatrix} = \begin{bmatrix} \bar{x}_{de} + \tilde{x}_{de} \\ \bar{x}_{qe} + \tilde{x}_{qe} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \bar{x}_{de} \\ \bar{x}_{qe} \end{bmatrix} = \begin{bmatrix} LPF & 0 \\ 0 & LPF \end{bmatrix} \begin{bmatrix} x_{de} \\ x_{qe} \end{bmatrix}, \quad \begin{bmatrix} \tilde{x}_{de} \\ \tilde{x}_{qe} \end{bmatrix} = \begin{bmatrix} HPF & 0 \\ 0 & HPF \end{bmatrix} \begin{bmatrix} x_{de} \\ x_{qe} \end{bmatrix} \tag{4}$$

B. AVM MODE

AVM is based on processing the rectangular wave shape of the load voltage with the phase angle information of the utility voltage provided that the harmonic isolation between the utility and the load is maintained. The method can be outlined by two processes: the fundamental component extraction and the voltage synthesis. In the fundamental component extraction process, the DC voltage quantity which represents the magnitude of the fundamental frequency component of the load voltage in the 'de' coordinate is found using the load voltage. In the voltage synthesis process, the load voltage in the rectangular wave shape and the fundamental frequency AC component of the load voltage waveforms are regenerated from the DC voltage quantity and the phase angle information. Lastly, the load harmonic voltage is obtained by the subtraction of the synthesized fundamental frequency component from the synthesized load voltage.

The phase angle (θ') to be used for processing the load voltage in AVM should be compensated for lead or lag caused by the circuit and the controller operation in order to increase the performance of the AVM. Consequently, the compensated phase angle information (θ') using the compensation time (T_θ) for the AVM is found to be in (5).

$$\theta' = \theta_e + \omega_e T_\theta = \theta_e + \omega_e\left(2T_S + t_{r,SRF} - \frac{L_S I_{S1}}{V_{S1}}\right) \tag{5}$$

1) SPAVM

In SPSAF, the block diagram of the AVM are illustrated in Fig1.3. Within the synthesis of v_L, the square waveform may be regenerated purely from VL,dc and θ' as given in (6). neither the v^{*}_{Lh} is correctly generated by the SAF. Thus, The synthesis with the linearization around $\theta' = 0$ and $\theta' = \pi$ using Tr is given in (7).

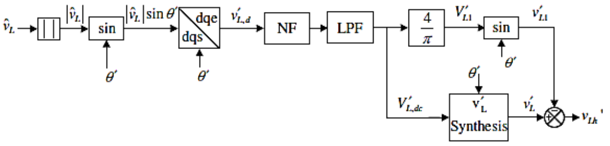

Fig.3. The SPAVM block diagram.

$$v'_L(\theta') = \begin{cases} V'_{L,dc} & ;0 \le \theta' < \pi \\ -V'_{L,dc} & ;\pi \le \theta' < 2\pi \end{cases} \tag{6}$$

$$v''_L(\theta')=\begin{cases} V'_{L,dc}\dfrac{\theta'}{\omega_e T_r} & ;0\le\theta'<\omega_e T_r \\ V'_{L,dc} & \omega_e T_r\le\theta'<\pi-\omega_e T_r \\ V'_{L,dc}\dfrac{\pi-\theta'}{\omega_e T_r} & \pi-\omega_e T_r\le\theta'<\pi+\omega_e T_r \\ -V'_{L,dc} & \pi+\omega_e T_r\le\theta'<2\pi-\omega_e T_r \\ V'_{L,dc}\dfrac{\theta'-2\pi}{\omega_e T_r} & 2\pi-\omega_e T_r\le\theta'<2\pi \end{cases} \tag{7}$$

2) *TPAVM*

TPAVM is more complex than SPAVM. The block diagram of AVM are illustrated in Fig. 4. The rules for the synthesis of the load phase voltages as pure six-step waveforms are given in (8) for each phase. In order to limit dv'_L/dt , T_r is bounded in the same manner as for the single-phase case. Therefore, a rate-of-change limiter, with simpler structure, is utilized per phase for TPAVM as shown in Figure 5 [13]. Considering inherent phase delays the rate of change limiter introduces at the rise and fall regions of pure six-step load voltage waveform, the input voltage of the rate-of- change limiter is modified as given in (9).

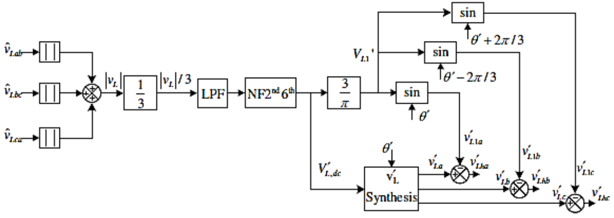

Fig.4. The TPAVM block diagram.

$$v''_{Labc}(\theta'')=\begin{cases} V'_{L,dc}/2 & ;0\le\theta''<\pi/3 \\ V'_{L,dc} & ;\pi/3\le\theta''<2\pi/3 \\ V'_{L,dc}/2 & ;2\pi/3\le\theta''<\pi \\ -V'_{L,dc}/2 & ;\pi\le\theta''<4\pi/3 \\ -V'_{L,dc} & ;4\pi/3\le\theta''<5\pi/3 \\ -V'_{L,dc}/2 & ;5\pi/3\le\theta''<2\pi \end{cases} \tag{8}$$

Where:

$$\theta''=\begin{cases} \theta' & ;v'_{Labc}=v'_{La}(\theta') \\ \theta'-2\pi/3 & ;v'_{Labc}=v'_{Lb}(\theta') \\ \theta'+2\pi/3 & ;v'_{Labc}=v'_{Lc}(\theta') \end{cases}$$

$$v''_{Labc}(\theta'')=\begin{cases} V'_{L,dc}/2 & ;-\omega_e T_r\le\theta''<\pi/3-\omega_e T_r/2 \\ V'_{L,dc} & ;\pi/3-\omega_e T_r/2\le\theta''<2\pi/3-\omega_e T_r/2 \\ V'_{L,dc}/2 & ;2\pi/3-\omega_e T_r/2\le\theta''<\pi-\omega_e T_r \\ -V'_{L,dc}/2 & ;\pi-\omega_e T_r\le\theta''<4\pi/3-\omega_e T_r/2 \\ -V'_{L,dc} & ;4\pi/3-\omega_e T_r/2\le\theta''<5\pi/3-\omega_e T_r/2 \\ -V'_{L,dc}/2 & ;5\pi/3-\omega_e T_r/2\le\theta''<2\pi-\omega_e T_r \end{cases} \tag{9}$$

Where:

$$\theta''=\begin{cases} \theta' & ;v'_{Labc}=v'_{La}(\theta') \\ \theta'-2\pi/3 & ;v'_{Labc}=v'_{Lb}(\theta') \\ \theta'+2\pi/3 & ;v'_{Labc}=v'_{Lc}(\theta') \end{cases}$$

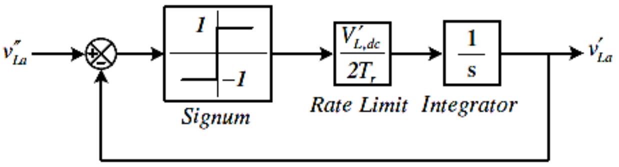

Fig.5. The per-phase diagram of the rate-of-change limiter for the load voltage synthesis in TPAVM.

VII. SIMULATION RESULTS

a) *SPSAF*

The load voltage regulation performance of SPSAF-CM is reported against two disturbance cases, which are utility voltage sag by 35% and load power increase by 20% are shown in Fig. 6 and Fig. 7, respectively.

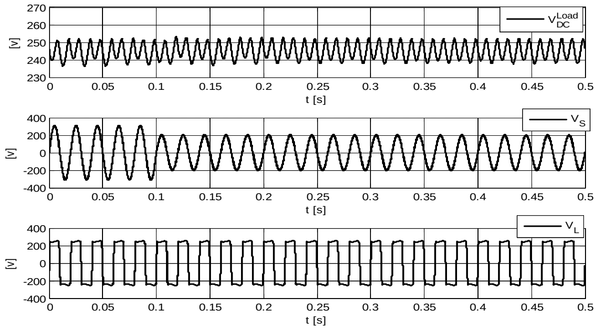

Fig.6. Load DC bus voltage (V_{DC}), line voltage (V_S) and load voltage (V_L) waveforms for 35% voltage sag (SPSAF-CM).

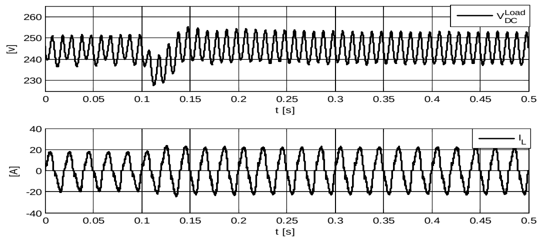

Fig.7. Load DC bus voltage (V_{DC}) and line current (I_L) waveforms for 20% load power increase (SPSAF-CM) .

The load voltage regulation performance of SPSAF-AVM is reported against two disturbance cases, which are utility voltage sag by 35% and load power increase by 20% are shown in Fig. 8 and Fig. 9, respectively.

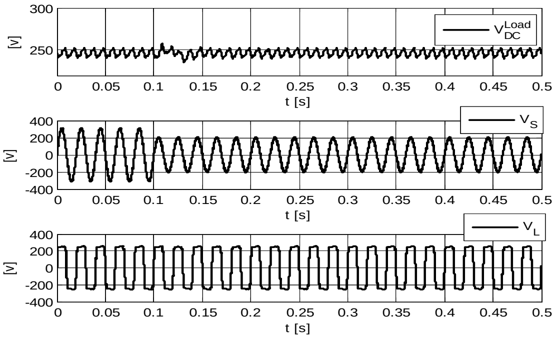

Fig.8. Load DC bus voltage (V_{DC}), line voltage (V_S) and load voltage (V_L) waveforms for 35% voltage sag (SPSAF-AVM).

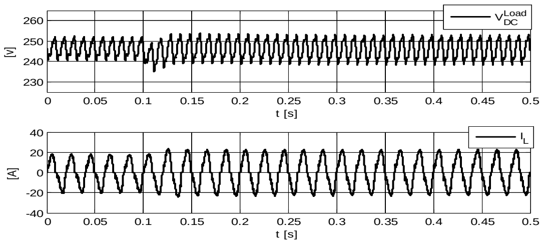

Fig.9. Load DC bus voltage (V_{DC}) and line current (I_L) waveforms for 20% load power increase (SPSAF-AVM) .

b) TPSAF

The load voltage regulation performance of TPSAF-CM is reported against two types of disturbances, which are three-phase balanced 35% utility voltage sag, and single-phase 35% utility voltage sag are shown in Fig. 10 and Fig. 11, respectively.

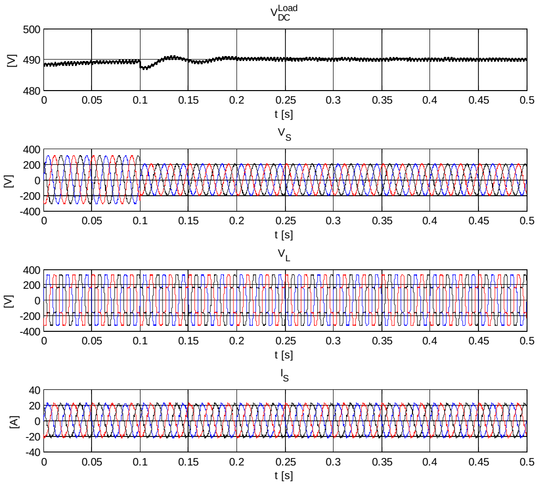

Fig.10. Waveforms for 35% balanced three-phase voltage sag. Top to bottom: Load DC bus voltage, three-phase utility voltages, three-phase load voltages, and three-phase line currents (TPSAF-CM).

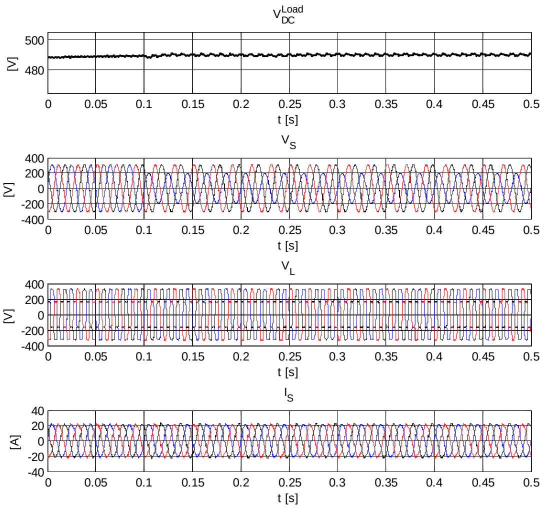

Fig.11. Waveforms for 35% single-phase voltage sag. Top to bottom: Load DC bus voltage, three-phase utility voltages, three-phase load voltages, and three-phase line currents (TPSAF-CM).

The load voltage regulation performance of TPSAF-AVM is reported against two types of disturbances, which are three-phase balanced 35% utility voltage sag, and single-phase 35% utility voltage sag are shown in Fig. 12 and Fig. 13, respectively.

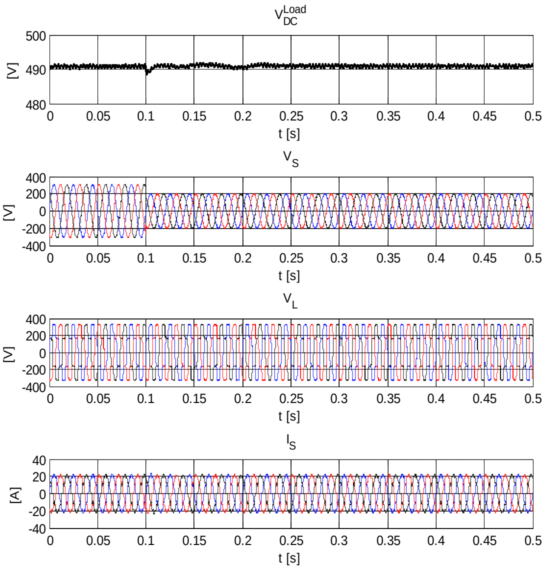

Fig.12. Waveforms for 35% balanced three-phase voltage sag. Top to bottom: Load DC bus voltage, three-phase utility voltages, three-phase load voltages, and three-phase line currents (TPSAF-AVM) .

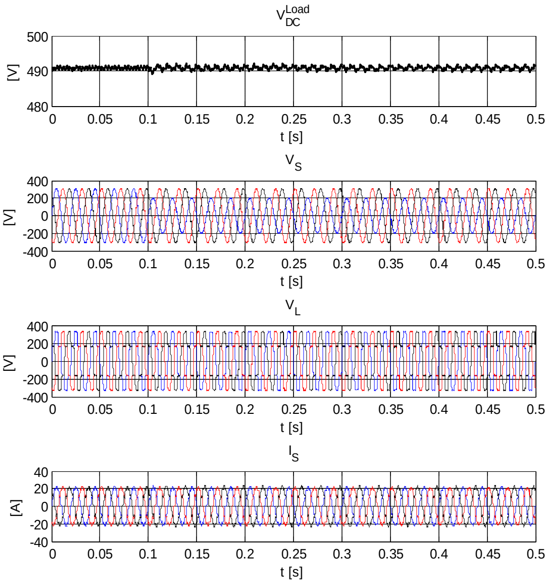

Fig.13. Waveforms for 35% single-phase voltage sag. Top to bottom: Load DC bus voltage, three-phase utility voltages, three-phase load voltages, and three-phase line currents (TPSAF-AVM).

VIII. PERFORMANCE COMPARISON

Increase conditions are tabulated in Table 1. As seen in the table, the SPSAF using AVM is superior to the SPSAF using CM such that the former has less voltage drops and shorter response times.

Table 1: The performance comparison between the load voltage regulation provided by the SPSAF using CM and AVM.

	CM		AVM	
	Feedback & Feedforward	**Only Feedback**	**Feedback & Feedforward**	**Only Feedback**
ΔV_{sag}(%)	0	12.2	0	4.4
Δt_{sag}(ms)	0	200	0	40
ΔV_{dyn}(%)	3.2	3.2	1.2	1.2
Δt_{dyn}(ms)	40	40	20	20

In order to compare the dynamic responses of the SAF with the cases discussed, the simulation results are tabulated in Table 2. As seen in the table the TPSAF employing AVM is superior to the TPSAF employing CM. It should be also noted that the feed forward controller improves the response of the SAF for voltage sags but not the load dynamics.

Table 2: The performance comparison between the load voltage regulation provided by the TPSAF using CM and AVM.

	CM		AVM	
	Only Feedback	**Feedback & Feedforward**	**Only Feedback**	**Feedback & Feedforward**
ΔV_{sag}(%)	10.5	0.6	6.1	0.5
Δt_{sag}(ms)	200	0	60	0
ΔV_{dyn}(%)	2.9	2.9	1.8	1.8
Δt_{dyn}(ms)	35	35	25	25
ΔV_{neg}(%)	1.2	0.4	1.2	0.3

IX. CONCLUSIONS

The Series Active Filter (SAF) is an active power quality conditioner for both utility and load related power quality problems such that it isolates the harmonic voltage of the load from the utility and regulates the load voltage against the line voltage disturbances. One of its advantageous features is that it is directly applicable to the voltage harmonic source type nonlinear loads without changing the load type to the harmonic current source type by adding extra inductances. The other major advantage is that in addition to harmonic isolation, it provides load voltage regulation against line voltage disturbances such as unbalances and sags which are common. The additional filtering elements utilized in the AVM extractor are to enhance its performance; however their dynamic responses are much faster than the CM case such that AVM provides a higher bandwidth harmonic extraction. The end result is that the whole system has higher steady-state performance and faster dynamic response yielding superior power quality compared to the CM case.

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