Harmonic Sources and Filtering Approaches
–Series/Parallel, Active/Passive, and Their Combined Power Filters–

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Abstract-This paper presents 22 configurations of power filters for harmonic compensation of nonlinear loads. Some of these configurations are novel and result from the newly discovered characteristics of nonlinear loads and circuitry duality, while the others are well known and used in practice. Nonlinear loads are characterized into two types of harmonic sources –current-source nonlinear loads and voltage-source nonlinear loads. These two types of harmonic sources have completely distinctive, dual properties and characteristics. Based on their properties and characteristics, the current-source nonlinear loads and voltage-source nonlinear loads have their own suitable filter configurations, respectively. This paper reveals 22 basic configurations: active and passive, series and parallel, and hybrid and combined power filters. Among them are some novel filter configurations, and their advantages are discussed and demonstrated by analysis, simulation, and experiment. In addition, a comprehensive comparison of all configurations is made in terms of required ratings, costs, performance, and controls.

I. INTRODUCTION

Traditionally, nonlinear loads have been represented as a current source because their current waveforms are distorted from pure sine-waves at fundamental frequency [1-8]. A typical harmonic source is a phase-controlled thyristor rectifier having a sufficient dc inductance to produce a non-pulsating dc current. Accordingly, parallel (or shunt) passive and parallel active filters are commonly applied to nonlinear loads to mitigate harmonics. The principle of the parallel passive filter is to provide a low-impedance shunt branch to the load's harmonic current, thus reducing harmonic current flowing into the source. The principle of the parallel active filter is to inject harmonic current with the same amplitude and opposite phase of the load's harmonic current into the line, thus eliminating harmonic current flowing into the source. Indeed, the parallel passive and active filters are effective for compensating such current-source nonlinear loads [9-20].

In recent years, more and more diode rectifiers with smoothing dc capacitors are used in electronic equipment, household appliances, and ac drives. Harmonics generated by these loads have become a major issue. However, a diode rectifier with smoothing dc capacitors behaves like a harmonic voltage source rather than a harmonic current source [9]. Accordingly, this type of nonlinear load has to be characterized as a voltage source. It has been shown that the parallel passive and active filters are not effective for compensating such voltage-source type of nonlinear loads [9, 10]. Instead, a series passive filter or a series active filter should be used to compensate for voltage-source nonlinear loads. In [9, 25], it has been shown that current-source nonlinear loads and voltage-source nonlinear loads have dual relations to each other in circuits and properties and that the parallel filters and series filters are suited for current-source and voltage-source loads, respectively.

Based on the preceding observation and on circuitry duality, this paper summarizes and presents 22 basic filter configurations that are suitable for compensating current-source and voltage-source nonlinear loads. Some novel filter configurations and their advantages are discussed and demonstrated by analysis, simulation, and experiment. In addition, a comprehensive comparison of all configurations is made in terms of required ratings, costs, performance, and controls.

II. TWO TYPES OF HARMONIC SOURCES

A. *Current-Source Nonlinear Loads (CSNLs)*

Thyristor converters are a common and typical source of harmonic currents. Fig. 1(a) shows a thyristor rectifier where a sufficient dc inductance produces a dc current. Fig. 2 shows the source voltage and rectifier current waveforms. The current waveform distortion (i.e., the generation of harmonics) results from the switching operation. Because the harmonic current contents and characteristics are less dependent on the ac side, this nonlinear load behaves like a current source. Therefore, it is called a current-source nonlinear load and represented as a current source shown in Fig. 1(b). Similarly, a diode rectifier with a sufficient dc inductance, a highly inductive load with SCR ac power control, etc., are current-source nonlinear loads.

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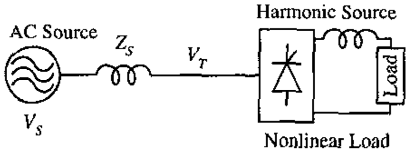
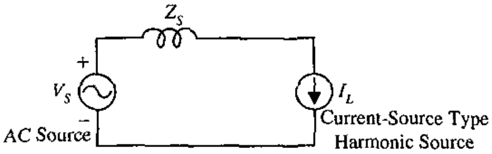


(a) Thyristor rectifier for dc drives, heater drives, etc.



(b) Per-phase equivalent circuit of thyristor rectifier.

Fig. 1. Typical current-source nonlinear load.

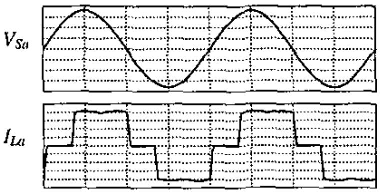
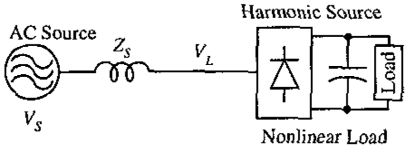


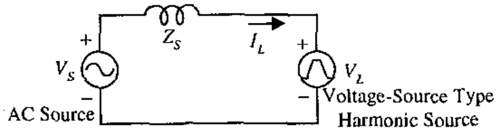
Fig. 2. Typical voltage and current waveforms of thyristor rectifier, source voltage V_{Sa} and line current I_{La}.

B. Voltage-Source Nonlinear Loads (VSNLs)

Another common type of harmonic source is a diode rectifier with smoothing dc capacitors, as shown in Fig. 3(a). Fig. 4 shows typical current and voltage waveforms. Although the current is highly distorted, its harmonic amplitude is greatly affected by the ac side impedance and source voltage unbalance, whereas the rectifier voltage (i.e., the voltage at the rectifier input terminal, as shown in Fig. 4) is characteristic and less dependent on the ac impedance. Therefore, the diode rectifiers behave like a voltage source rather than a current source. Fig. 3(b) shows the equivalent circuit of the diode rectifier system where the diode rectifier is represented as a harmonic voltage source (or voltage-source nonlinear load). It has been shown in [9, 25] that a parallel active filter (PAF) or a parallel passive filter (PPF) is not effective for compensating for such voltage-source nonlinear loads.



(a) Diode rectifier for ac drives, electronic equipment, etc.



(b) Per-phase equivalent circuit of diode rectifier.

Fig. 3. Typical voltage-source nonlinear load.

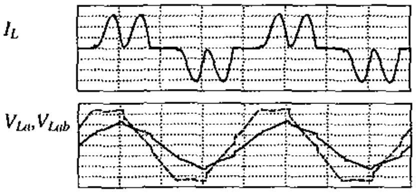


Fig. 4. Typical current and voltage waveforms of diode rectifier, line current I_L, line-to-neutral voltage V_{La}, and line-to-line voltage V_{Lab} at rectifier input.

III. POWER FILTER CONFIGURATIONS

Based on the preceding characterization of nonlinear loads, 22 filter configurations can be derived, as shown in Figs. 5 through 26. Although Figs. 5, 7, 9, 11, 13, 19, 21, 23, and 25 are well-known configurations and Figs. 6, 8, and 15 are less known, Figs. 10, 12, 14, 16, 17, 18, 20, 22, 24, and 26 are novel and newly presented in this paper. It is noted that Figs. 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, and 25 are dual to Figs. 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, and 26, respectively. This dual relationship originates from the duality of the two types of harmonic sources and the circuits. It is evident that other combinations and modifications based on these 22 basic configurations are possible. For example, Figs. 13 and 14 can be modified using the dominant harmonic active filter technique [27].

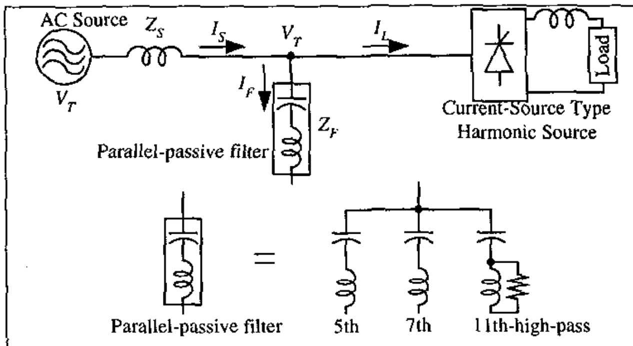


Fig. 5. Basic parallel-passive filter for current-source nonlinear loads.

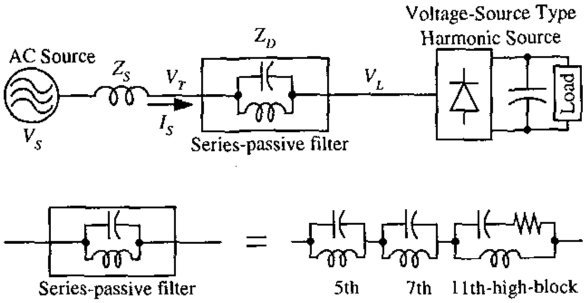


Fig. 6. Basic series-passive filter for voltage-source nonlinear loads.

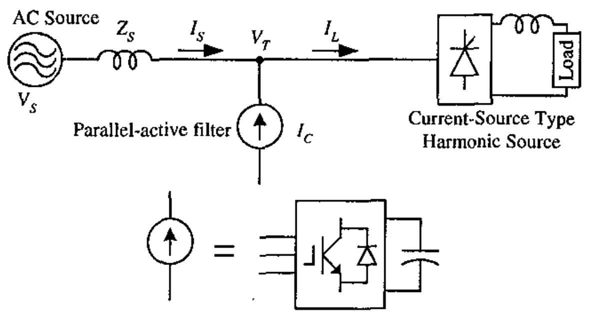


Fig. 7. Basic parallel-active filter for current-source nonlinear loads.

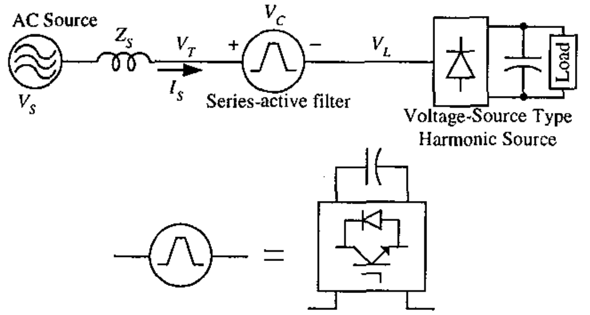


Fig. 8. Basic series-active filter for voltage-source nonlinear loads.

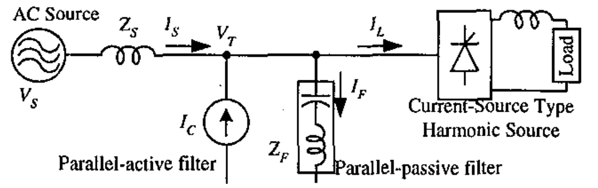


Fig. 9. Parallel combination of parallel-active and parallel-passive filters for current-source nonlinear loads.

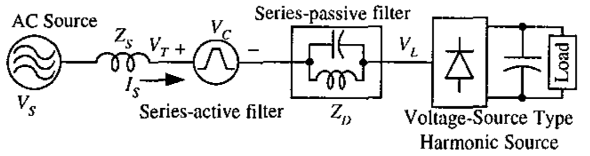


Fig. 10. Series combination of series-active and series-passive filters for voltage-source nonlinear loads.

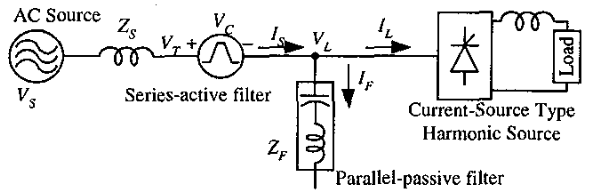


Fig. 11. Hybrid of series-active and parallel-passive filters for current-source nonlinear loads.

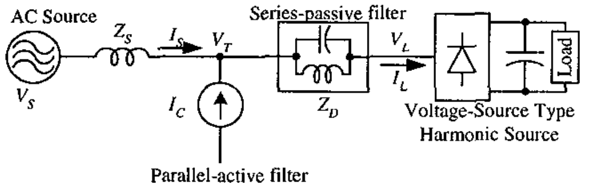


Fig. 12. Hybrid of parallel-active and series-passive filters for voltage-source nonlinear loads.

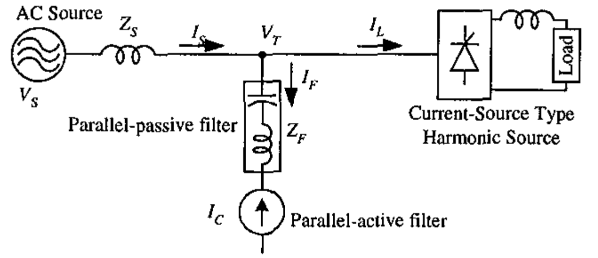


Fig. 13. Series combination of parallel-passive and parallel-active filters for current-source nonlinear loads.

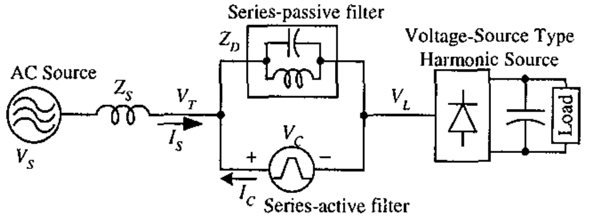


Fig. 14. Parallel combination of series-passive and series-active filters for voltage-source nonlinear loads.

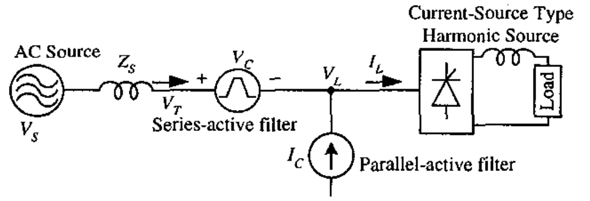


Fig. 15. Combined system of series-active and parallel-active filters for current-source nonlinear loads.

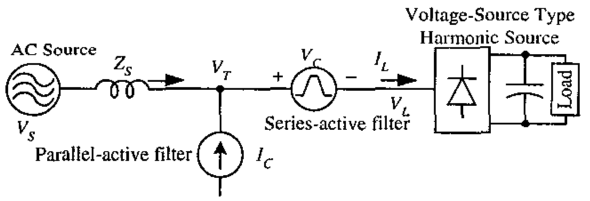


Fig. 16. Combined system of parallel-active and series-active filters for voltage-source nonlinear loads.

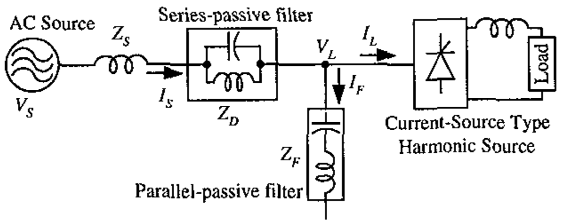


Fig. 17. Combined system of series-passive and parallel-passive filters for current-source nonlinear loads.

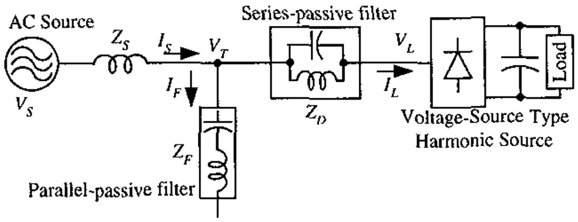


Fig. 18. Combined system of parallel-passive and series-passive filters for voltage-source nonlinear loads.

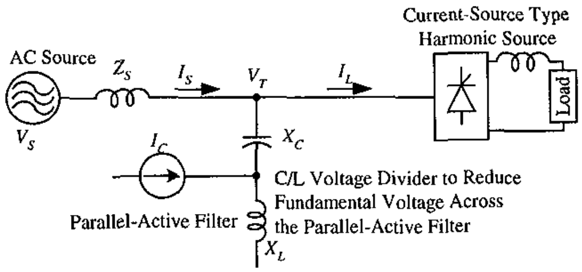


Fig. 19. Circuit I to reduce fundamental voltage of parallel-active filter.

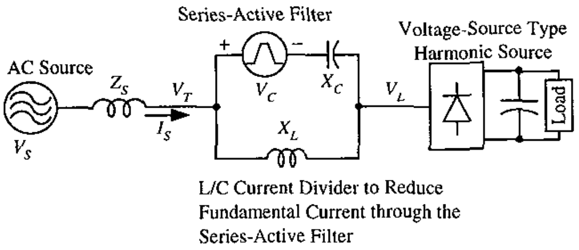


Fig. 20. Circuit I to reduce fundamental current of series-active filter.

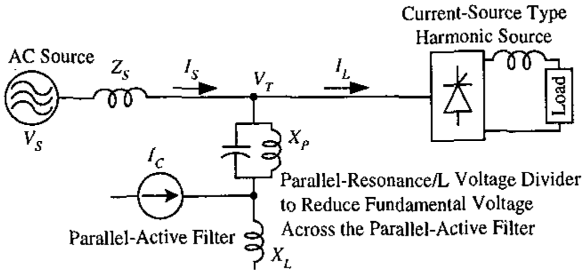


Fig. 21. Circuit II to reduce fundamental voltage of parallel-active filter.

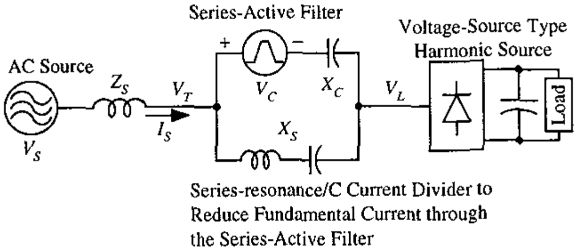


Fig. 22. Circuit II to reduce fundamental current of series-active filter.

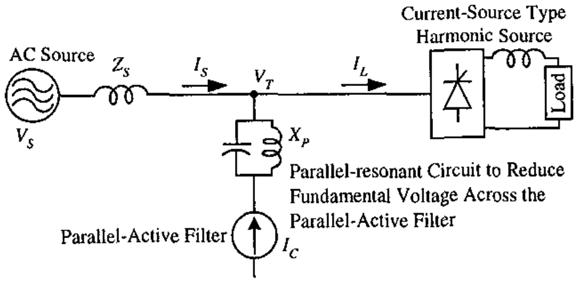


Fig. 23. Circuit III to reduce fundamental voltage of parallel-active filter.

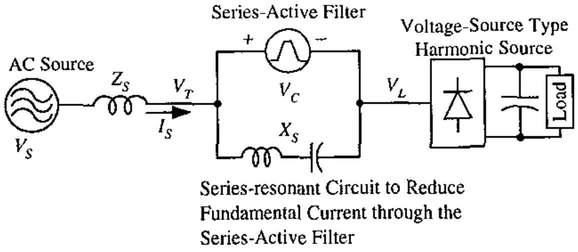


Fig. 24. Circuit III to reduce fundamental current of series-active filter.

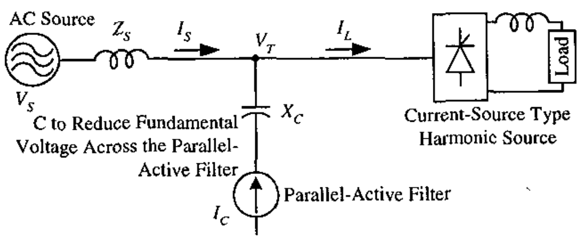


Fig. 25. Circuit IV to reduce fundamental voltage of parallel-active filter.

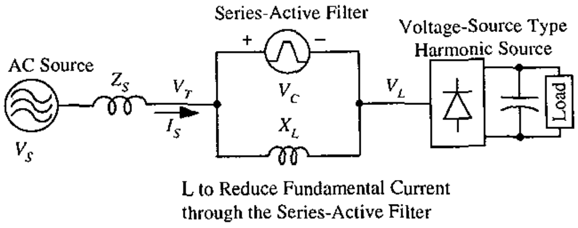


Fig. 26. Circuit IV to reduce fundamental current of series-active filter.

IV. OPERATING PRINCIPLE, CONTROL SCHEMES, COMPARISON, AND EXPERIMENTAL RESULTS

A. Basic Operating Principle of Parallel and Series Filters

Fig. 5 shows the basic configuration of a PPF. The PPF provides low impedance branches consisting of series-resonant LC circuits, each tuned at a harmonic frequency, and/or high-pass LCR circuits to the load or harmonic current source, thus acting as a harmonic current sink. The ultimate circuit of the PPF is only a capacitor. Fig. 6 shows the basic configuration of a series-passive filter (SPF). Contrary to the PPF, the SPF provides high-impedance blocks to the load or harmonic voltage source, thus acting as a harmonic current dam. In Fig. 6, an SPF consisting of a 5th-parallel-resonant circuit, a 7th-parallel-resonant circuit, and an 11th-high-block circuit connected in series is shown as an example [25]. The 5th-and 7th-tuned parallel resonance provides high impedance, respectively, to block the 5th and 7th harmonic current flow. The 11th-high-block circuit is tuned at the 11th order to provide high impedance to the 11th harmonic current and harmonic current above the 11th. The ultimate circuit of the SPF is an inductor.

Fig. 7 shows the basic configuration of a PAF. The PAF injects harmonic current to the line with the same amplitude of and opposite phase to the load's harmonic current, thus acting as a harmonic current source to cancel the load harmonic current. Fig. 8 shows the basic configuration of a series-active filter (SAF) [23, 24]. Contrary to the PAF, the SAF provides harmonic voltage with the same amplitude of and opposite phase to the load harmonic voltage, thus acting as a voltage source to block harmonic current flow. A voltage-source inverter or a current-source inverter can be used for the PAF or SAF. As examples, a voltage-source inverter is shown in both Fig. 7 and Fig. 8.

Fig. 9 shows the parallel combination of a PAF and a PPF for current-source nonlinear loads. The PAF is more suited for the compensation of low-order harmonics (e.g., 5th and 7th) than high-order harmonics (above 11th) because of limited switching frequency and rating, whereas the PPF is more suited and compact for the compensation of high order harmonics. Therefore, it would be good role sharing in this combined system for the PAF to compensate low-order harmonic current and for the PPF to compensate high-order harmonic current. In addition, the PAF can be used to eliminate the resonance between the source and the PPF. Fig. 10 shows the series combination of an SAF and an SPF for voltage-source nonlinear loads. Similarly, the SAF and SPF can share compensation roles and be used to block low-order harmonics and high-order harmonics, respectively.

Fig. 11 shows a hybrid system of a small SAF and a PPF for current-source nonlinear loads [21, 22]. The small SAF is used to eliminate the PPF's problems (such as resonance and influence of the source impedance) and enhance compensation performance. The PPF sinks the load harmonic current. Fig. 12 is Fig. 11's dual circuit, a hybrid system of a PAF and a SPF for voltage-source nonlinear loads. Contrary to Fig. 11, the SPF in Fig. 12 blocks harmonic current and the PAF can be used to enhance the SPF's performance and eliminate the SPF's resonance.

Fig. 13 shows the series combination of a PPF and a PAF, where the PAF injects harmonic current to cancel the load harmonics and provides fundamental current so that the line voltage is applied to the PPF and no fundamental voltage appears on the PAF. As a result, the required VA rating of the PAF is reduced and the combined system still provides as excellent performance as does a PAF. Fig. 14 is Fig. 13's dual circuit, the parallel combination of an SAF and an SPF. Similarly, the SAF's VA rating is reduced by letting fundamental current flow through the SPF.

Fig. 15 shows an ideal filter configuration for current-source nonlinear loads. The PAF injects harmonic current to cancel the load harmonic current, whereas the SAF blocks harmonic current from flowing through the line. This filter system not only can eliminate harmonic current but also can provide pure sinusoidal and constant voltage V_T to the load, even when the source voltage is distorted and fluctuating. Fig. 16 is the dual system of Fig. 15, ideal for a harmonic voltage-source load. The system blocks harmonic current and provides pure sinusoidal voltage V_T to all loads connected at V_T.

Figs. 17 and 18 show the respective combination of passive filters for harmonic current-source loads and harmonic voltage-source loads.

Active filters are expensive and have difficulties with high power applications, although their performance is superior. It is desirable to reduce active filters' required rating. Figs. 19 through 26 show examples of how to reduce fundamental voltage across the PAF and fundamental current through the SAF. For example, Fig. 19's C and L form a voltage divider to reduce fundamental voltage across the PAF. The fundamental voltage across the PAF is determined by the impedance ratio of C and L. Fig. 20 shows the dual circuit of Fig. 19, where C and L form a current divider to reduce fundamental current of the SAF. In Fig. 21, an LC parallel circuit resonating at the fundamental frequency is used to increase the impedance ratio and reduce the fundamental voltage further. On the contrary, Fig. 22 uses an LC series circuit resonating at the line frequency, thus further reducing the SAF's fundamental current. In Figs. 23 and 25, fundamental voltage across the PAF can be reduced to zero by controlling the PAF's injected fundamental current. Similarly, in Figs. 24 and 26, fundamental current through the SAF can be reduced to zero by controlling the SAF's produced fundamental voltage.

B. Control and Comparison of Parallel and Series Filters

Control schemes, circuit designs, application considerations, and the main features of all configurations are summarized in Table 1.

Table 1 Summary and Comparison of the Filters♠

Fig.	Operating Principle /Suited Nonlinear Loads	Circuit Design and Control Scheme	Features, Performance, and Considerations	VA Ratings /System Cost
5	Harmonic sink /CSNL	Low-impedance circuit or series-resonant circuit	Resonance with and influenced by the source impedance	Var+harmonic current, i.e., $V * (I_{var} + I_{Lh})$ /cheapest
6	Harmonic dam /VSNL	High-impedance circuit or parallel resonant circuit	No resonance with and no bad influence by the source	Fundamental+harmonic voltage, i.e., $I * (V_{df} + V_{Lh})$ /cheapest
7	Current source/ CSNL	PAF injects current so that $I_C = I_{Lh}$	Ideal performance to CSNL	$V * I_{Lh}$ /expensive
8	Voltage source /VSNL	SAF produces voltage $V_C = -V_{Lh}$	Ideal performance to VSNL	$I * V_{Lh}$ /expensive
9	Current source+harmonic sink /CSNL	PAF: low-order harmonic compensation & resonance damping; PPF: high-order harmonic compensation	Good performance, compensation role sharing, dynamic var compensation possible	PAF: $V * I_{Lh(5,7)}$ PPF: $V * (I_{var} + I_{Lh(11,13,\ldots)})$ /fairly expensive
10	Voltage source+harmonic dam /VSNL	SAF: low-order harmonic compensation and damping; SPF: high-order harmonic compensation	Good performance, compensation role sharing, dynamic voltage regulation possible	SAF: $I * V_{Lh(5,7)}$ SPF: $I * (V_{df} + V_{Lh(11,13,\ldots)})$ /fairly expensive
11	SAF: harmonic isolation PPF: harmonic compensation /CSNL	SAF: blocking harmonic current PPF: low-impedance circuit	Ideal performance, dynamic voltage regulation possible	SAF: $I * I_{Lh}Z_F$, minimized VA rating, PPF: $V * (I_{var} + I_{Lh})$ /minimized system cost
12	PAF: harmonic isolation SPF: harmonic blocking /VSNL	PAF: eliminates upstream & adjacent harmonics so that no harmonics appear at the terminal voltage V_T SPF: high impedance circuit	Ideal performance, dynamic var compensation possible by PAF	PAF: $V * I_{h(upstream+adjacent)}$, SPF: $I * (V_f + V_{Lh})$ /minimized system cost
13	PAF: enhancing PPF and resonance damping PPF: harmonic compensation /CSNL	PAF is controlled so that load harmonic current is absorbed completely by the PPF PPF: low-impedance circuit	Ideal performance to CSNL, source harmonic voltage will appear at the terminal V_T	PAF: $(I_{var}+I_{Lh})*I_{Lh}Z_F$, minimized VA, PPF: $V * (I_{var} + I_{Lh})$ /minimized system cost
14	SAF: enhancing SPF SPF: harmonic blocking /VSNL	SAF: helping to block harmonic current, $V_C \approx -V_{Lh}$ SPF: high-impedance circuit	Ideal performance to VSNL, no harmonic resonance	SAF: $V_{Lh}*V_{Lh}/Z_D$, minimized VA, SPF: $I * (V_f + V_{Lh})$ /minimized system cost
15	SAF: harmonic isolation PAF: harmonic compensation /CSNL	SAF: harmonic isolation, source harmonic compensation, and voltage regulation; PAF: load harmonic compensation	Ideal performance to CSNL, dynamic voltage regulation and var compensation possible	SAF: $I * V_{Sh}$, PAF: $V * (I_{var} + I_{Lh})$ /most expensive
16	SAF: harmonic compensation PAF: harmonic shunting /VSNL	SAF: load harmonic compensation; PAF: shunt to upstream & adjacent harmonics	Ideal performance to VSNL, dynamic var compensation possible	SAF: $I * V_{Lh}$, PAF: $V * I_{h(upstream\ and/or\ adjacent)}$ /most expensive
17	SPF: harmonic isolation PPF: harmonic compensation /CSNL	SPF: for harmonic isolation and source harmonic compensation; PPF: for load harmonic compensation	Better performance than PPF alone, V_T becomes sinusoidal even when V_{Sh} exists	SPF: $I * V_{Sh}$, PAF: $V * (I_{var} + I_{Lh})$ /cheap
18	SPF: harmonic compensation PPF: harmonic shunting /VSNL	SPF: load harmonic compensation; PPF: provides shunt to adjacent harmonic loads	Make the terminal voltage V_T more sinusoidal when source and adjacent harmonics exist	SPF: $I * V_{Lh}$, PPF: $V * I_{h(upstream\ and/or\ adjacent)}$ /cheap
19 21 23 25	Use LC circuits to reduce fundamental voltage applied on PAF /CSNL	Fundamental voltage of the PAF can be reduced to $X_L/(X_C + X_L)$ in Fig. 19, to $X_L/(X_P + X_L)$ in Fig.21, and to zero in Figs. 23 and 25. On the other hand, harmonic current injected by the PAF will cause harmonic drop over X_C or X_P.	An optimum design is desirable to minimize the total VA rating of PAF and total system cost. Dynamic var compensation not possible	Fig. 19: $(V X_L/(X_C+X_L)+I_{Lh}X_C)* I_{Lh}$ Fig. 21: $(V X_L/(X_P+X_L) + I_{Lh}X_P)* I_{Lh}$ Fig. 23: $I_{Lh}X_P*(I_{Lh}+V/X_P)$ Fig. 25: $I_{Lh}X_C*(I_{Lh}+V/X_C)$
20 22 24 26	Use LC circuits to reduce fundamental current flowing through SAF /VSNL	Fundamental current of the SAF can be reduced to $X_L/(X_C + X_L)$ in Fig. 20, to $X_L/(X_S + X_L)$ in Fig. 22, and to zero in Figs. 24 and 26. On the other hand, harmonic voltage produced by the SAF will cause harmonic current over X_C or X_P.	An optimum design is desirable to minimize the total VA rating of SAF and total system cost. Dynamic voltage regulation not possible	Fig. 20: $(I X_L/(X_C+X_L)+V_{Lh}/X_L)* V_{Lh}$ Fig. 22: $(V X_L/(X_S+X_L)+V_{Lh}/X_S)* I_{Lh}$ Fig. 24: $V_{Lh}/X_S*(V_{Lh}+I X_S)$ Fig. 26: $V_{Lh}/X_L*(V_{Lh}+I X_L)$

♠ The symbols used in this table are explained as follows: I_{Lh} is the load harmonic current, V_{Lh} is the load harmonic voltage, V is the load terminal voltage rating, I is the load current rating, V_f and I_f are fundamental voltage and current, I_{var} is the PPF's reactive current, V_{df} is the fundamental voltage drop on Z_D, Z_F is the PPF's impedance, Z_D is the SPF's impedance, etc.

C. Experimental Results of Series Filters

Figs. 27 and 28 show experimental results of an SPF for a diode rectifier. The SPF consists of a 5th-parallel resonant circuit, a 7th-parallel-resonant circuit, and an 11th-high-block circuit. The 0.6% source impedance is inherent in the line. The SPF not only made the current sinusoidal but also reduced the ripple on the dc link of the rectifier.

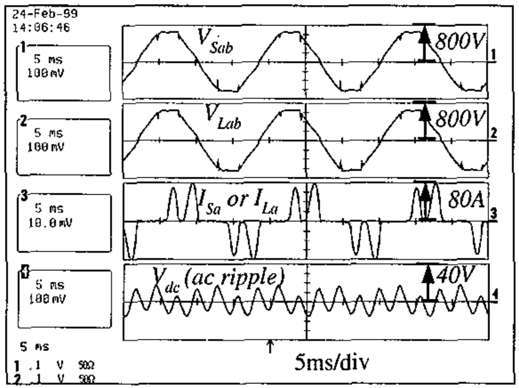


Fig. 27. Experimental waveforms of a diode rectifier without a series-passive filter (Z_S=0.6%).

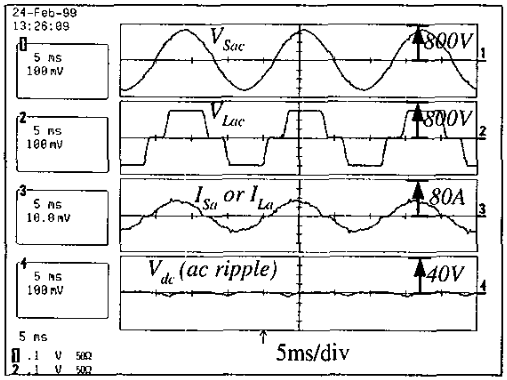


Fig. 28. Experimental waveforms of the diode rectifier with a series-passive filter (Z_S=0.6%).

Figs. 29 and 30 show experimental results of an SAF used to block harmonic current of a diode rectifier. The SAF is controlled to provide high impedance to the harmonics. Accordingly, the output voltage reference of the series-active filter is given as $V_C^*=K \cdot i_{Sh}$, where i_{Sh} is the source harmonic current extracted through a notch filter and K is the gain. With the SAF, the source current I_{Su} became pure sinusoidal and in phase with the phase voltage V_{Sa}. The SAF's VA rating is 25% of the load. In [9], a detailed discussion and comparison have been given for SAFs and PAFs.

The parallel combination (Fig. 14) of an SAF and an SPF can block harmonic current more effectively than the SAF or SPF alone. This combined system provides many features that cannot be obtained by either an SAF or an SPF alone. Figs. 31 and 32 show waveforms. The combined system provides equivalently infinite impedance to harmonics, thus resulting in a purer sine-wave current compared with the case of the series passive filter only. Fig. 32 shows that the source current I_{Sa} flows through the SPF and that only minimized harmonic current is provided by the SAF to enhance compensation effects. In addition, the SAF's VA rating is only 4% of the load VA rating, which is much lower than the case of the SAF alone.

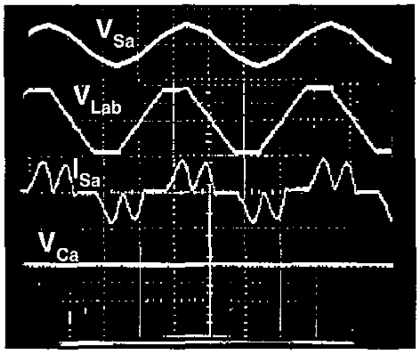


Fig. 29. Experimental waveforms of diode rectifier without a series-active filter (Z_S=3%, V_{Sa}, V_{Lab}:635V/div, I_S: 200A/div, V_{Ca}:254V/div, time:5ms/div).

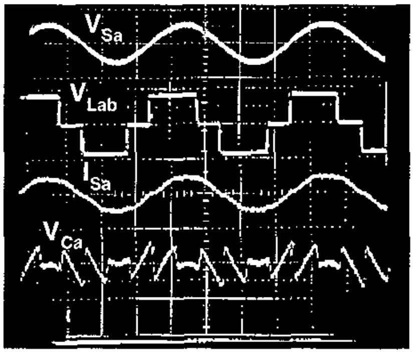


Fig. 30. Experimental waveforms of diode rectifier with a series-active filter (Z_S=0.6%, V_{Sa}, V_{Lab}: 635V/div, I_S: 200A/div, V_{Ca}:254V/div, time:5ms/div).

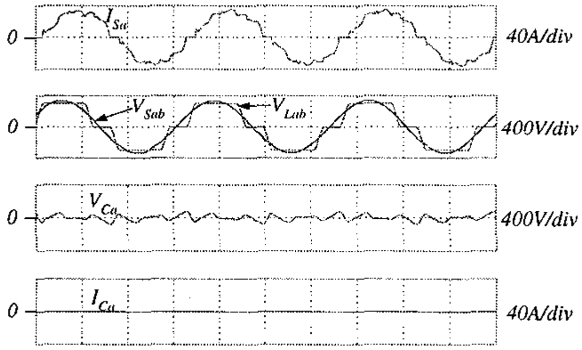


Fig. 31. Experimental waveforms for a diode rectifier with only a series-passive filter.

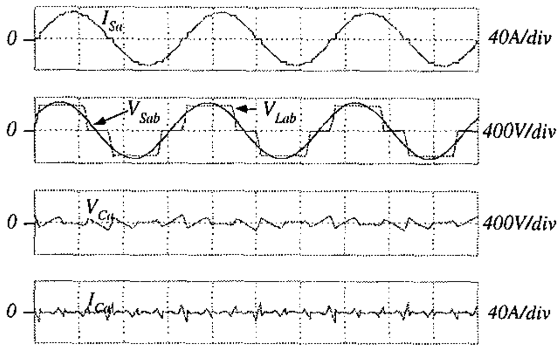


Fig. 32. Experimental waveforms for the diode rectifier with the combined system (Fig. 14) of a series-passive filter and a series-active filter.

V. CONCLUSIONS

This paper presented 22 configurations of power filters for harmonic compensation of nonlinear loads. Some of these configurations are novel and result from the newly discovered characteristics of nonlinear loads and circuitry duality, while the others are well known and used in practice. Nonlinear loads can be characterized into two types of harmonic sources – current-source nonlinear loads and voltage-source nonlinear loads. These two types of harmonic sources have completely distinctive and dual properties and characteristics. Based on their properties and characteristics, the current-source nonlinear loads and voltage-source nonlinear loads have their own suitable filter configurations, respectively. This paper revealed and summarized 22 basic configurations: active and passive, series and parallel, and hybrid and combined power filters. Their operating principles are discussed in detail. A comprehensive comparison of all configurations has been made in terms of required ratings, costs, performance, and controls. Experimental results demonstrated the principle of SAFs/SPFs and their combined systems suited for voltage-source nonlinear loads.

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