Comparison of Structure Topologies for Hybrid Filters

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Abstract-**The hybrid filter is a combination of a passive filter and a small-rated active filter, which gives a relatively economical approach comparing to a conventional active filter. The initial cost and the operation switching loss of the filter are proportional to the rating of the active filter. Different structures of passive filters in a hybrid filter have different required ratings of the active part of the hybrid filter. Based on the pervious researches, there are many different topologies of a hybrid filter. They can be mainly classified as: Series-Type, b-Shape and Parallel-Type Hybrid Filters. In this paper, a comparison among different structure topologies of Hybrid Filters is performed. The guidelines are given for the selection of Hybrid Filter topologies. Computed and simulated results show out its validity of the discussion in this paper.**

I. INTRODUCTION

In this paper, a shunt connected hybrid power filter is considered for reactive, harmonic and unbalance current compensations in distribution sides of power networks. Pervious papers [1]~[3] proposed a combined system, called a Hybrid Filter, of a passive filter and a small-rated active filter for a practical and economical way for the current quality compensation. However, different structures of Hybrid Filters were proposed, which can be mainly classified into series-type, b-shape type and parallel-type hybrid filters. In this paper, a series-type hybrid filter [4]~[6] is defined as a series combination of passive filters and an active filter together as shown in Fig. 1. In Fig. 2, a b-shape type [7][8] is defined as 2 passive filters connected in series and one of them is in parallel with an active filter. Finally, in Fig. 3, a parallel-type [9][10] is defined as a passive filter is in parallel with a series combination of a passive filter and an active filter together. The pervious papers [7][8] proposed that the b-shape type hybrid filter can reduce the required rating of the active part of the hybrid filter. However, based on papers [7][8], the DC linked voltage is 250V when the system voltage is 220V line-to-line voltage, which is obvious that the experimental rating is larger than the theoretical one. In this paper, a comparison among those 3 different topologies is performed. The results indicate that the b-shape type hybrid filter is not the lowest required rating one for the active part of the hybrid filters for both dynamic reactive and harmonic compensations. Furthermore, the parallel-type one cannot reduce the rating of the active part of the hybrid filter for harmonic compensation. Computed and simulated results show out its validity of the discussion in this paper.

II. DISCUSSION CRITERION

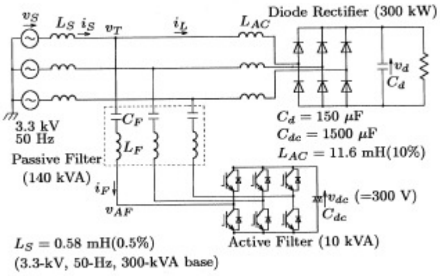

Fig. 1. Series-Type Hybrid Filter[6]

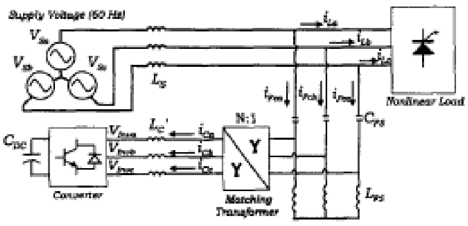

Fig. 2 b-Shape Type Hybrid Filter[8]]

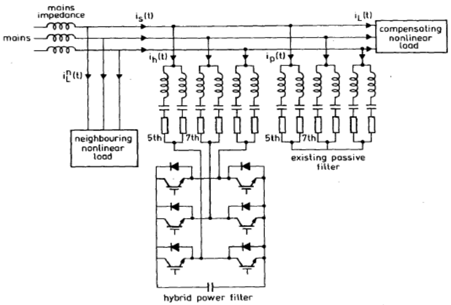

Fig. 3 Parallel-Type Hybrid Filter[9]

The hybrid filter is dedicated for compensation of oscillating power which is composed of fundamental reactive power and harmonic power. Based on the power quality measured results in Macao, it found that fundamental reactive power is the dominant oscillating power. Due to the fact that fundamental and harmonic powers are operating at different frequencies, the analysis can be considered as 2 parts: fundamental reactive and harmonic compensations. The research direction is to determine a structure to have the lowest rating of the active part of a hybrid filter under compensation of fundamental reactive current and harmonics.

The harmonic compensation ability changes according to the selected structure of the passive filter. Reversely, the power capacity of the active filter may change according to the passive filter structure. Finally, the required power rating is given as (1), where Q_1 is the required fundamental reactive power, I_{Ln} is the load current and Z_{PFn} is the impedance of the passive filter at harmonic order n respectively.

$$S_{AF} = \sqrt{Q_1^2 + \sum_{n=2}^{\infty} \left(Z_{PFn} I_{Ln} \right)^2} \qquad (1)$$

Different topologies of the hybrid filter are compared for a same specific load which is a three-phase rectifier with a highly inductive load and its harmonic components are listed in Table I. For simplicity, the rms load current is assumed to be 1 A.

TABLE I
CURRENT HARMONIC COMPONENTS AND THD EXPRESSED AS HARMONICS-TO-FUNDAMENTAL CURRENT AMPLITUDE

Order	3	5	7	11	13	17	19	THD
%	0	20	14.3	9.1	7.1	5.9	5.3	31.1

The lowest rating in the active part of the hybrid filter can reduce the switching loss and its initial cost. By comparing required rating given in (1) for the same specific load, a comparison among different structure topologies of Hybrid Filters can be performed in the following sections.

III. COMPARISON OF DIFFERENT STRUCTURE TOPOLOGIES

A. *Series Type Hybrid Filter*

An equivalent circuit of the series-type hybrid filter can be expressed as Fig. 4. The passive part of the hybrid filter, Z_{PFU}, can be inductive or capacitive. If the passive part is inductive, it is the conventional active filter. Fig. 5 shows a phasor diagram when the inductive-coupled active filter is operated under a capacitive mode for inductive reactive power compensation. It is obvious that the terminal voltage of the inverter, V_I , needs to be larger than the terminal coupling voltage V_L. In another case, the Z_{PFU} is capacitive. Fig. 6 shows a phasor diagram when the capacitive-coupled hybrid filter is operated under capacitive mode. The required inverter voltage can be smaller than terminal coupling voltage V_L. From the above discussion, the rating of the active part of the hybrid filter can be smaller by a capacitive-coupled hybrid filter.

The coupling impedance Z_{PFU} can be chosen as an inductive, a capacitive, a single-tuned LC resonance, or a multi-tuned LC circuit. Under the same required fundamental reactive power, based on (1), it founds that the required system rating is proportional to the frequency response of the Z_{PFU}. Fig. 7 shows the impedance comparison among different passive filters under the same fundamental reactive power. The tuned resonance frequencies are chosen to be harmonic order 5 and 7 respectively.

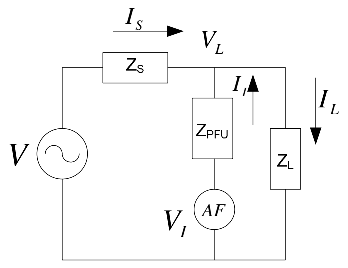

Fig. 4 A Single-Phase Series-Type Equivalent Circuit

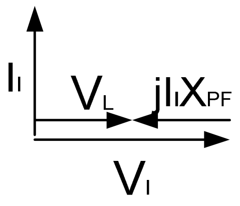

Fig. 5 Phasor Diagram for an Inductive-Coupled Active Filter

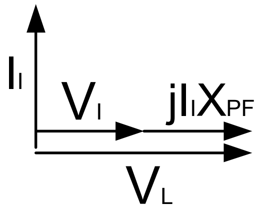

Fig. 6 Phasor Diagram for a Capacitive-Coupled Hybrid Filter

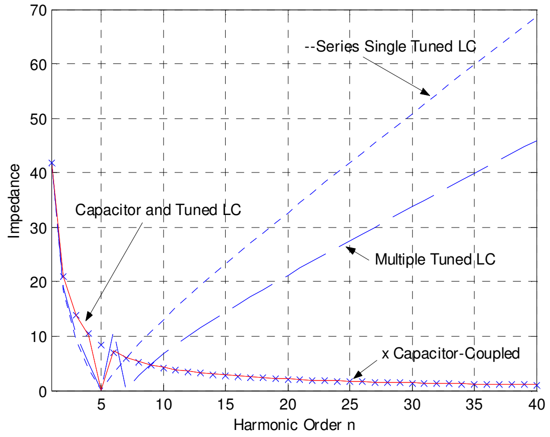

Fig. 7 Impedance comparison among different passive filters under the same fundamental reactive power

The inductive Z_{PFU} increases the higher order component impedance and required rating for compensation, which increases the operating frequency of the switching devices and the switching loss. Table II shows the computed required rating for different cases. When the inductive-coupled filter is assumed to be the reference, the Capacitor and Tuned LC Hybrid Filter needs only 1.06% of the power rating of the conventional active filter and switching frequency range of the inverter is lower than other cases. However, in practical cases, the series-pure-capacitor with the inverter may cause ripple current due to the rate of change of voltage generated by an inverter. Finally, the passive part of the hybrid filter is shown in Fig. 8, where C_R and L_R should be designed according to the largest load harmonic order, and then a small L_1 can be determined based on the ripple limit of the injected compensated current, and finally C_1 can be calculated according to the required fundamental reactive power.

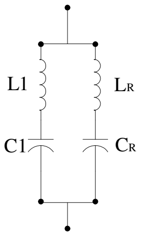

Fig. 8 Passive Part of the Series-Type Hybrid Filter

TABLE II
COMPARISON OF DIFFERENT PASSIVE FILTER DESIGN FOR A SERIES-TYPE HYBRID FILTER

Z_{PFU}	Inductive (Active Filter)	Capacitive	Single-Tuned LC (5th Order)	Multi-Tuned LC (5th & 7th)	Capacitive and a Tuned LC (5th Order)
%	100	2.89	2.28	1.28	1.06

B. *b-Shape Hybrid Filter*

In a b-shape hybrid filter, an impedance Z_{PFL} is connected in parallel with an active filter. An equivalent circuit is shown in Fig. 9. Based on the above section, the capacitive-coupled impedance, Z_{PFU}, can have the lower rating in the active part of the filter. As a result, the following discussion is performed under the capacitive Z_{PFU} assumption. The paralleling impedance, Z_{PFL}, can be inductive or capacitive. The first part of the discussion is for the fundamental reactive power compensation, and then the second part is for harmonic compensation. Finally, a summary is given.

For the fundamental reactive power compensation, the required reactive power is given in (2). In (2), R and Q_b can be expressed as (3) and (4). However, R is a variable parameter, which is depended on the required reactive power, Q, for compensation. Q_{c0} is a supported reactive power by Z_{PFU} for a single-phase path. Normally, Q is negative due to a common inductive load assumption. As a result, R is negative for an inductive load. Furthermore, the first term of (2) can be considered as the required fundamental reactive power supported by a Series-Type Hybrid Filter. The second term of (2) is important to analyze the required reactive power rating, which can be considered as an extra-reactive power. Q_b can be defined as the addition required reactive power when a parallel path to the inverter is given.

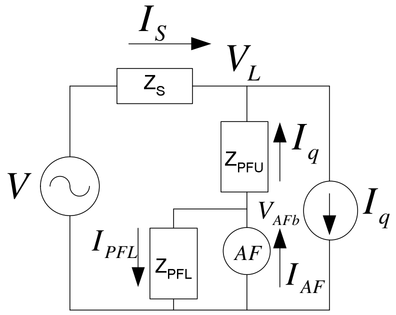

Fig. 9 A Single Phase b-Shape Equivalent Circuit

When the load is inductive, the required compensated reactive power is negative. The first term of (2) will be negative, however, if the second term of (2) is positive so that the Q_{AFb} can be smaller. In ideal case, Q_{AFb} can be zero if first term and second term are equal but in opposite signs, which is the reason why the b-type parallel inductor hybrid filter can reduce the required reactive power when R is not equal to 1. However, the parallel-inductor should be large so that the required rating can be smaller. Table III shows a simulation result. Paralleling a capacitor increases the rating, and a high inductor can decrease the rating.

$$Q_{AFb} = -(1-R)V_L I_q + (1-2R+R^2)Q_b \qquad (2)$$

$$R = \frac{Q}{3Q_{co}} \qquad (3)$$

$$Q_b = \begin{cases} \dfrac{V_L^2}{\omega L_{PFL}} & when \quad Q_b > 0 \\ -\omega C_{PFL} V_L^2 & when \quad Q_b < 0 \end{cases} \qquad (4)$$

TABLE III
COMPARISON OF SERIES-TYPE AND b- SHAPED HYBRID FILTERS FOR FUNDAMENTAL REACTIVE POWER COMPENSATION
(Voltage=100v, Frequency =50Hz, R=5Ω , L=20mH)

C_{PFU}= 143.3uF	Series-Type Capacitive (VAR)	b-Shape Paralleling an Inductor L_{PFL}=0.03H (VAR)	b-Shape Paralleling an Inductor L_{PFL}=0.3H (VAR)	b-Shape Paralleling a Capacitor C_{PFL}=3.8uF (VAR)
Required Rating (R=1)	0.494	0.493	0.494	0.144
Required Rating (R=-4.32)	9723	12282	6999	11990

For the harmonics compensation, the required apparent power for a specific harmonic component is given in (5).

$$S_{bn} = Z_{PFUn} I_{qn}^2 + Z_{PFUn} I_{qn} I_{PFLn}^* \qquad (5)$$

There are 2 parts in (5). The first term is the same as the series-type case; the second term is the additional power that is passing through the parallel path of the b-type hybrid filter. Furthermore, (5) can be expressed as (6), where the symbol * means complex conjugate.

$$S_{bn} = (1 + \frac{Z_{PFUn}^*}{Z_{PFLn}^*}) Z_{PFUn} I_{qn}^2 \qquad (6)$$

The term, Z_{PFUn}^* / Z_{PFLn}^*, is important when it is negative and smaller than 1, the final apparent power rating can be smaller. However, in the parallel inductor case, when the number of harmonic order increases, the term turns to be near to zero so that the lower order harmonic components may be reduced by this factor. But, it does not affect the higher order harmonic components. And, when L_{PFL} is very small, the final apparent power can be smaller. On the other hand, in a parallel capacitor case the number of harmonic order increases, the term will increase so that higher order harmonic components will be increased by the factor. As a result, the final apparent power will turn to be larger. Table IV summaries a computed result.

TABLE IV
Comparison of b-Shaped Hybrid Filters For Harmonic Compensation

b-Shape Paralleling an Impedance	Without L_{PFL}	L_{PFL}= 1H	L_{PFL}= 0.05H	C_{PFL}= 1mF	C_{PFL}= 0.1uF
Required Apparent Power (VAR)	13.16	13.13	12.47	190.88	13.18

There is a contradiction to fundamental reactive power and harmonic compensations in the b-shape type parallel inductor hybrid filter as it requires a very large inductor for fundamental reactive power compensation and requires a small inductor for harmonic compensation in order to reduce the required rating of the active part of the hybrid filter. When the system is only needed to compensate the harmonic power, adding a small inductor in parallel as the b-shape type hybrid filter can reduce the rating of active part of the hybrid filter. However, it is not appreciated for the fundamental reactive power compensation, which needs higher rating. The pervious papers [7][8] proposed that the b-shape type hybrid filter can reduce the required rating of the active part of the hybrid filter, which is corrected only for the harmonic compensation. When a b-shape hybrid filter with a parallel inductor Z_{PFL} needs to compensate the fundamental reactive power and harmonic components at the same time, the required power is increased mainly due to the increase of the required rating for the fundamental reactive power compensation. However, in a practical system, the dominant oscillating power is the fundamental reactive power.

To reduce the required rating of the active part of the hybrid filter, the ratio of load reactive power to total reactive power supported by the series impedance, Z_{PFU}, should be designed near to one another (R=1). When R=1 based on (2), adding a parallel Z_{PFL} impedance does not reduce the total required rating of the active part of the Hybrid Filter.

C. *Parallel-Type Hybrid Filter*

In a parallel-type hybrid filter, an impedance Z_{PFP} is connected in parallel with the filter. An equivalent circuit is shown in Fig. 10. Based on the above section, the capacitive-coupled impedance, Z_{PFU}, can have the lower rating in the active part of the filter. As a result, the following discussion is performed under the capacitive Z_{PFU} assumption.

For the fundamental reactive power compensation, the required reactive power is given in (7).

$$S_{AFP} = -j(1 - R + \frac{Q_P}{Q_{C0}})V_L I_q \qquad (7)$$

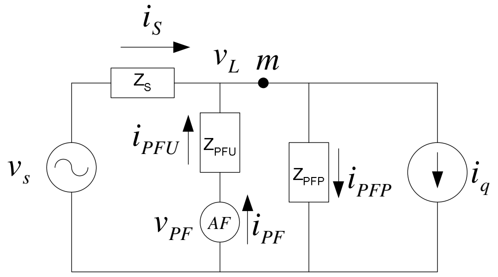

Fig. 10 A Single Phase Parallel-Type Equivalent Circuit

The required rating can be zero if $Q=3Q_{C0} + 3\ Q_P$ can be achieved, where Q is the three-phase total load reactive power, Q_{C0} is the single-phase fundamental reactive power supported by the passive filter, Q_P is the single-phase parallel fundamental reactive power supported by the parallel passive filter, Z_{PFP}. The parallel passive filter, Z_{PFP}, can reduce the fundamental reactive current passing through the Hybrid Filter so that the required rating of the active part of the hybrid filter can be lower. However, when R=1 is settled during design stage, the parallel passive filter is not necessary. Simulation tests are performed and summarized in Table V. Based on the calculation result, when C_{PFP} = 238uF, the required rating of the active filter can be smaller. In Table V, Z_{PFP} should not be inductive. The inductive Z_{PFP} increases the required fundamental reactive power. As a result, there is no inductive Z_{PFP} in the Table V. The parallel passive filter, Z_{PFP}, can perform par of the fundamental reactive power compensation and the remained part can be compensated by the active part of the Hybrid Filter.

TABLE V
Comparison of Series-Type and Parallel-Type Hybrid Filters For Fundamental Reactive Power Compensation
(Voltage=100v, Frequency =50Hz, R=5Ω , L=20mH)

Z_{PFP}	Series-Type Capacitive (VAR)	Parallel-Type C_{PFP}=309.7uF (VAR)	Parallel-Type C_{PFP}=238uF (VAR)	Parallel-Type C_{PFP}=51.6uF (VAR)
Required Rating R=-4.32	3241.2	358.9	1.58	221.5

For the harmonics compensation, the required apparent power is given in (8), where Z_{Sn} is the source impedance.

$$S_{AFP} = \sqrt{\sum_{n=2}^{\infty} \left(\frac{Z_{PFPn}}{Z_{PFPn} + Z_{Sn}} Z_{PFUn} I_{Ln}^2 \right)^2} \qquad (8)$$

Based on the above discussion, an inductor is connected in parallel with the Hybrid Filter, which increases the required fundamental reactive power for compensation and is unprofitable so that the inductive case is ignored for discussion. Only parallel capacitive and resonance-tuned cases are considered as follows.

When the parallel path is a capacitor, (8) can be changed into (9), where L_S is the inductance impedance of the source such as the transmission lines and C_{PFP} is the parallel capacitance. Obviously, the resonance should be avoided between the source inductance and the parallel capacitance. However, the value of C_{PFP} is determined by the required fundamental reactive power.

$$S_{Ln} = \frac{1}{1 - n^2 \omega^2 L_S C_{PFP}} Z_{PFn} I_{Ln}^2 \qquad (9)$$

When the parallel path is a series combination of a capacitor and an inductor, (9) can be changed into (10). When the resonance is happened in the parallel path only, the required apparent power can be zero. Comparing the series–type cases, it seems that there is no advantage by choosing the Resonance-Tuned Filter in parallel case. The required rating is the same as the series-type as Z_{PFUn} can be zero at resonance. The power rating cannot be reduced, but the cost is increased under the view point of harmonic compensation.

$$S_{Ln} = \frac{n\omega L_{PFP} - \frac{1}{n\omega C_{PFP}}}{n\omega(L_{PFP} + L_S) - \frac{1}{n\omega C_{PFP}} +} Z_{PFn} I_{Ln}^2 \qquad (10)$$

A computed test is performed for a Single-Tuned LC case; it got the same result, 2.28%, as shown in Table III. By comparing the Series-Type and Parallel-Type Hybrid Filters for harmonic compensation, adding a parallel path, Z_{PFP}, cannot reduce the required rating of the active filter.

IV. GUIDELINES AND SUMMARY

In series-type hybrid Filters, a capacitor-coupled hybrid filter is more preferable than an inductor-coupled hybrid filter (the conventional active filter) as it needs lower voltage than the conventional one so that the rating of the active part of the hybrid filter can be smaller. A capacitor and tuned LC Hybrid Filter should be chosen as shown in Fig. 8 if the dominant oscillating power is the fundamental reactive power. Under the same reactive power condition, it needs relatively about 1% of the active part power rating of the conventional active power for harmonic compensation. The total reactive power supported by the passive filter should be the same as the load required (R=1). In order to reduce the overshoot current in the capacitor, a small inductance should be in series with the capacitor. The resonance tuned LC filter should be selected according to the highest load harmonic component.

In b-Shape Hybrid Filters, L_{PFL} should be large for fundamental reactive power compensation and L_{PFL} should be small for harmonic compensation, which contradicts one another. However, if R is already 1, based on (2), there is no influence to required rating of the fundamental reactive power compensation by adding a parallel L_{PFL}. In R=1 and the load is unchangeable, adding a small L_{PFL} is a solution to reduce the required rating for harmonic compensation. However, when R is not equal to 1 and to add a small L_{PFL}, it may increase the total rating for reactive compensation. However, normally fundamental reactive power is the dominant component of the oscillating power in an electric network. As a result, in dynamic compensation applications, adding L_{PFL} is not an appreciated approach for Hybrid Filter applications as it can reduce the harmonic compensation rating, but it increases the fundamental reactive power compensation rating.

In parallel-Type Hybrid Filters, when the reactive power supported by the series passive filter is not matched to the loads, adding a parallel capacitive passive filter with the Hybrid Filter can reduce the required rating of the active part of the Hybrid Filter. However, resonance between the source inductance and the parallel passive filter should be avoided. For harmonic compensation, there is no advantage to reduce the rating of the active part of the hybrid filter.

V. CONCLUSION

When all the oscillating powers including fundamental reactive power, harmonic power and unbalanced power are needed for compensation dynamically, the series capacitive-coupled Hybrid Filter is the appreciated circuit configuration for compensation with R =1 and LC resonance at highest load harmonic component However, when only harmonic power is the main concern for compensation and when the fundamental reactive power loads are steady, the b-shape paralleling a small inductor hybrid filter is the appreciated structure. Nevertheless, the parallel-type one can be employed in a case that a series-type hybrid filter is installed before based on R=1 and then initial reactive power load is changed into another operating value so that a parallel-path, Z_{PFP}, can be used for reactive power compensation adjustment so that it can reduce the rating of the active part of the Hybrid Filter.

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