Hybrid Compensation Arrangement in Dispersed Generation Systems

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***Abstract*—This paper presents a hybrid compensation system consisting of an active filter and distributed passive filters. In the system, each individual passive filter is connected to a distortion source and designed to eliminate main harmonics and supply reactive power for the distortion source, while the active filter is responsible for the correction of the system unbalance and the cancellation of the remaining harmonics.**

The paper also analyzes the effects of the circuit configuration on the system impedance characteristics and consequently the effectiveness of the filter system. Simulation studies are performed for a power system including the dispersed generation units connected into the system through power electronic converters and diode rectifier loads, which produce the distorted waveforms. The simulation results have demonstrated that good compensation effects can be achieved by using the combined filter system consisting of distributed passive filters and an active filter.

***Index Terms*—Active filter, dispersed generation, distributed passive filters, hybrid compensation, impedance characteristics.**

I. INTRODUCTION

AN electrical system often supplies consumers with various types of loads, including nonlinear loads, such as single-phase and/or three-phase thyristor converters, diode rectifiers and uninterruptible power supplies. These nonlinear loads may produce harmonics and system unbalance and may also consume reactive power. The power quality of ac systems can be deteriorated, if a proper compensation is not in place.

The situation becomes more serious with the development of the dispersed generation (DG) where power electronic converters are often used to interface the generation units, such as wind turbines and fuel cells etc. The power electronic interfaces may generate harmonics and require reactive power (e.g., SCR converters). Also the types and levels of the distortions may vary with the operation conditions of the dispersed generation units and the loads; therefore, an effective compensation system is required to maintain the power quality.

Passive filters have the features of low cost and good efficiency and have been widely used to absorb harmonic current of nonlinear loads. They can also provide reactive power to improve the power factor. However, passive filters suffer some drawbacks, such as strong dependence on system impedance, susceptible to source and load resonance and the characteristic variation due to aging. Also passive filters are often designed with fixed parameters, which cannot be easily adapted for the varying operation conditions and are difficult to correct the system unbalance.

Active power filters [1], including series and shunt active filters, have been developed to compensate the drawbacks of passive filters. Active filters are flexible and can provide excellent compensation for voltage and current distortions, but are not a cost-effective solution yet due to the high construction and operation costs. Consequently, hybrid filter topologies, such as the combination of series active and parallel passive filters [2] and active filter in series with parallel passive filters [3]–[5] have been developed to combine the advantages of passive filters and active filters for cost effective compensation.

The parallel connection of passive filters with an active filter has been discussed previously [6], [7], where one passive filter and one active filter are connected in parallel, the arrangement has shown the effectiveness to deal with the distortion under a varying operation condition. This paper extends the concept into a system consisting of a group of distributed passive filters and one active filter, which can effectively compensate the distortion in a local network, such as a local DG system or a wind farm.

The system configuration will be presented with a brief description of the operation of the filter system, then the filters are described. The variations of the impedance characteristics due to the change of the system configuration, i.e., the connection of the shunt passive filters and loads/dispersed generation units, are to be presented. Furthermore, simulation studies are presented, analyzed and discussed.

II. SYSTEM CONFIGURATION

The configuration of the studied system is illustrated in Fig. 1, where the passive filters are distributively connected near the loads/dispersed generation units in the system and an active filter is connected at a central connection point, for example, a substation. Each passive filter may be designed according to the distortion characteristics of the load/dispersed generation unit that the passive filter is connected to, and the active filter is in parallel with the passive filters and loads/dispersed generation units.

In operation, the passive filters compensate for the major harmonics at a position near the load or generation unit. Therefore, the harmonic flow is limited and the harmonic impact, such as interference to communications and increase in power loss, are to be effectively reduced.

The active filter is located at the upstream position to remove the remaining harmonics and corrects the unbalance of the system.

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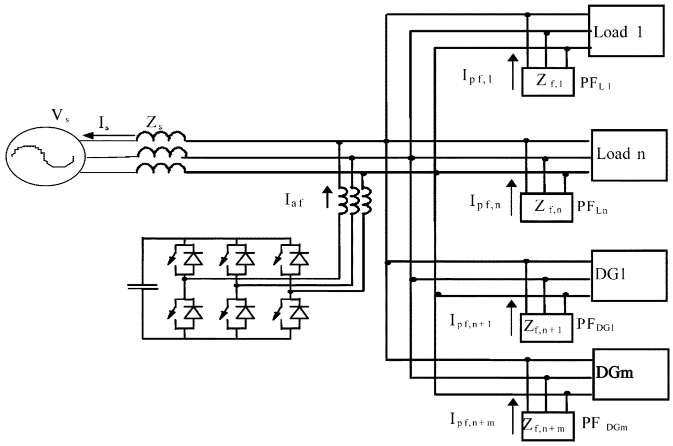

Fig. 1. Schematics of a parallel connected hybrid compensation arrangement in a system with dispersed generation (DG) units.

The filter configuration presents a feature of the relatively independent compensation; either the passive filters or the active filter may operate independently within the designed capacity whether other filters are in operation or not.

III. Filter Systems

A. Passive Filters

Passive filters often provide a harmonic sink, the low impedance path at certain frequencies, to divert some current harmonics. For a six pulse thyristor converter load, the passive filter may be designed with branches tuned to 5th and 7th harmonic frequencies and a high pass branch for the higher frequency harmonics. A typical shunt filter, including the single tuned filters for 5th and 7th harmonics and a damped filter for higher order harmonics, is shown in Fig. 2. Fig. 3 shows the impedance frequency characteristic of the filter, where the parameters are based on the system in [6]. The supply ac system is assumed to have an inductive characteristic as shown by the dashed line in Fig. 3, while the passive filters tuned to 5th, 7th and higher harmonics present the characteristics shown in the solid line.

It can be clearly seen that the passive filter circuit has lower impedance than the system impedance at the tuned frequencies (5th and 7th harmonics) and a range of designed higher frequencies so as to provide a bypass branch to the load harmonic current at these frequencies. The lower the harmonic impedance of the passive filters in comparison with the system impedance, the better the harmonic filtering performance. Obviously due to the presence of fundamental voltage, the passive filter bank can also generate fundamental frequency reactive power.

Each group of passive filters in Fig. 1 may be designed on the basis of the characteristics of the load/dispersed generation unit that the filter is connected to. According to the harmonic distribution and the possible range of the reactive power of the load/dispersed generation unit, the passive filters will be designed to provide a low impedance path for the major harmonics and also to compensate some reactive power, for example, making a unity power factor for an average operation condition [6].

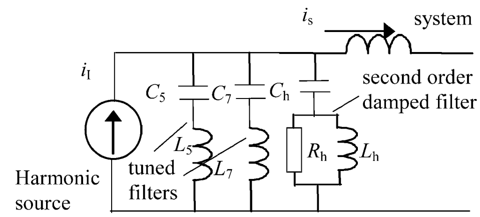

Fig. 2. Shunt passive filters for current harmonic source.

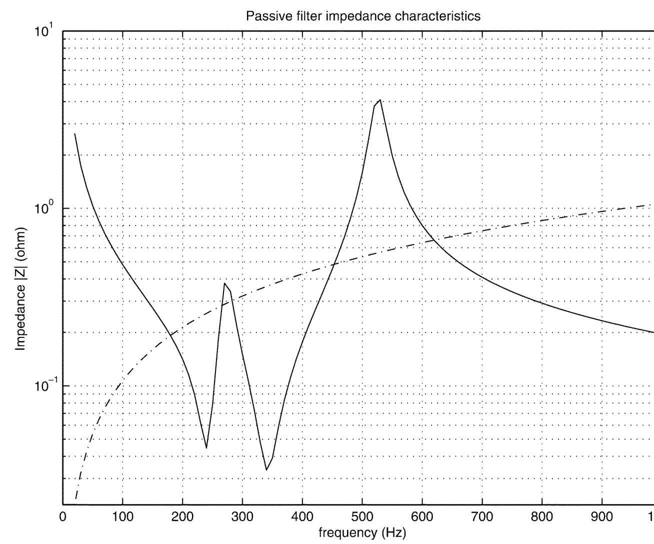

Fig. 3. Shunt passive filter characteristic.

B. Active Filter

Active power compensators or active filters are modern applications of power electronic converters. These converters can be controlled to cancel the harmonics by generating a harmonic current or voltage in opposite phase to the harmonic current or voltage to be corrected. There are basically two types of filter configurations, parallel compensation and series compensation. In a parallel compensation system, the compensator is normally connected to the circuit in parallel and injects a compensation current at the connection point. On the other hand, a series compensator is connected into the circuit in series, usually through a transformer, to insert a compensation voltage into the circuit. Normally, the thyristor converter discussed in the paper is considered as a harmonic current source, naturally, the parallel compensation system is the choice.

An active filter connected to the system in parallel is shown in Fig. 4. The active filter is responsible for the central compensation of the local network, it can also correct the unbalanced system current and further minimize the current harmonics into the main ac system. Within the rating limit, the active filter may also provide some reactive power regulation to the supply system if it is designed and required to do so.

The active filter will be controlled to follow the system operation condition to provide flexible compensation. In order to reduce the rating of the active filter, a further hybrid configuration, such as connecting a passive filter in series with the active filter [3], may be adopted.

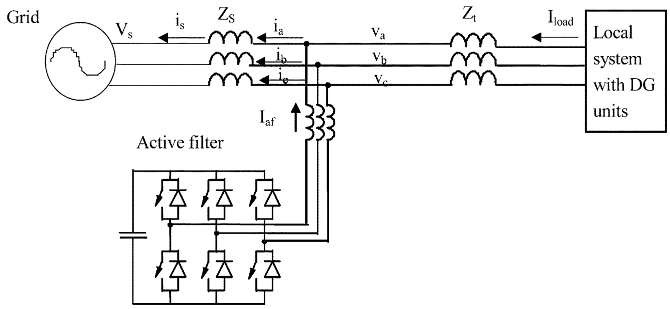

Fig. 4. An active filter for a current harmonic source.

C. Control of the Active Filter

The passive filters can be switched in or out together with the corresponding load/dispersed generation unit, or they may be put into operation in independence from the associated load/dispersed generation unit, if necessary. These passive filters normally cannot be controlled on-line, therefore, the only active control is with the active filter.

The control techniques of active filters have been studied by many researchers. Various control methods based on frequency domain or time domain have been developed and reported in literature, such as the instantaneous power theory, the synchronous rotating reference frame method, and the FFT based control method. These control schemes produce a current reference waveform, $i_{\mathrm{af.ref}}$, which is compared with the measured current. Then the active filter is driven by the difference between the two waveforms to generate the desired compensation waveform. The instantaneous power theory based method [1] is used in this paper. In the instantaneous power theory, the instantaneous real and reactive power p and q can be decoupled as dc components, $\bar{p}$ and $\bar{q}$, and ac components, $\tilde{p}$ and $\tilde{q}$. The fundamental power is represented by dc components, $\bar{p}$ and $\bar{q}$, and the harmonics correspond to the ac components, $\tilde{p}$ and $\tilde{q}$. Different compensation schemes can be obtained by choosing the components to be eliminated, such as harmonic elimination only or reactive power plus harmonic compensation [6]. A schematic representation of the used control system is illustrated in Fig. 5.

IV. System Impedance Characteristics

A. System Description

The connection of multiple passive filters into the system modifies the system impedance characteristics and therefore may affect the effectiveness of the filtering system and possibly cause system resonance. Therefore, it is important to investigate the system impedance characteristics in order to avoid such undesirable effects.

Harmonic sources can be generally divided into two types, voltage harmonic sources and current harmonic sources. The filter systems connected in parallel (Figs. 2 and 4) are effective to divert harmonic currents and therefore useful for current harmonic sources. However, if a voltage harmonic appears in the system within the frequency range tuned by the passive filters, then the voltage harmonic may result in a significant amount of

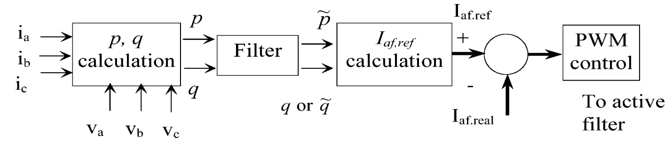

Fig. 5. Block diagram of control system for the active filter.

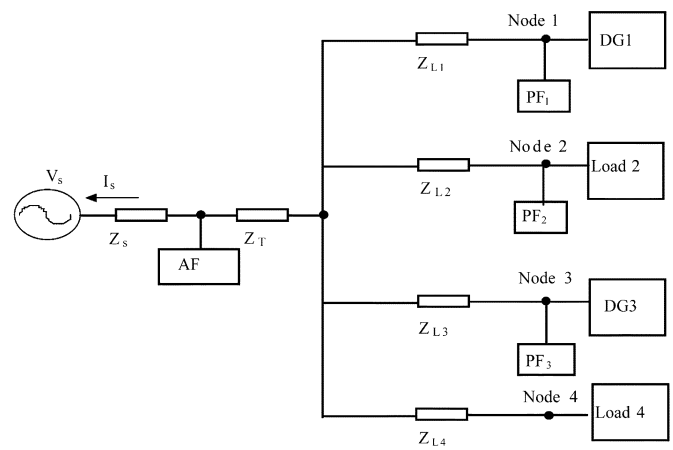

Fig. 6. Studied system configuration with dispersed generations and distorted load.

harmonic current. In such a situation, the appropriate filters, series filters either active or passive, may be required to provide compensation for the voltage harmonic source.

An example system is used for illustration of the impedance characteristic study. The configuration of the example system is shown in Fig. 6. There are two DG units (DG1 and DG3) and two loads (Load 2 and Load 4). The DG1 and DG3 are interfaced via the thyristor converter, which is one type of possible DG interfacing configurations; Load 2 contains unbalanced diode rectifiers loaded inductively. Therefore, the DG1, DG3 and Load 2 may be considered as current sources in terms of harmonic distortion. For simplification, the three groups of DG/load are such arranged that three passive filters (PF_1, PF_2 and PF_3) may use the same parameters having the characteristics shown in Fig. 3 and are connected at nodes 1, 2, and 3 for DG1, DG3 and Load 2.

Load 4 is a three phase rectifier system with a capacitive dc load, hence it is a voltage source in terms of harmonic distortion. The parallel filter described above may not be suitable for it, an LCL type filter may be required, however, that type filter is not to be discussed in this paper and it is assumed that no filter is used for Load 4 in Fig. 6. Further details about the system can be found in Table I.

The loads/dispersed generation units are connected into the system through three phase power lines with the parameters given in [8]. The lines are represented by $Z_{L1}(R: 0.2625\ \Omega, L: 0.635\ \mathrm{mH})$, $Z_{L2}(R: 0.525\ \Omega, L: 1.3\ \mathrm{mH})$, $Z_{L3}(R: 0.7875\ \Omega, L: 1.9\ \mathrm{mH})$ and $Z_{L4}(R: 0.1313\ \Omega, L: 0.318\ \mathrm{mH})$ respectively. The system side parameters are $L_s = 0.01$ mH and $L_t = 0.16$ mH (the resistance is ignored) for the supply and transformer respectively. To study the system impedance characteristic variations, the system equivalent impedance characteristics viewed from different locations are computed. Such impedance analyzes are performed

TABLE I
LOAD/DG PARAMETERS AND CONDITIONS FOR THE SYSTEM STUDIED

Identifier	Components of load /DG unit	Associated passive filters	Load/source current (kA)	Current THD (%)	Load current unbalance ($I_{2(1)}/I_{p(1)}$ %)
DG1	Three phase thyristor converter, (extinction angle 58°)	PF_1	0.812 (DC side)	28	balanced
Load 2	Three unbalanced single phase diode rectifiers	PF_2	0.554,0.689,0.588 (AC rms)	13.59, 13.98, 3.55	8.2
DG3	Three phase thyristor converter, (extinction angle 38°)	PF_3	0.838 (DC side)	28	balanced
Load 4	Three phase diode rectifiers			Capacitive dc link	balanced

TABLE II
CIRCUIT IMPEDANCE VIEW POINT AND CONFIGURATION

Viewed from Node 1	No parallel branch Branch 2 in parallel Branches 2 and 3 in parallel Branches 2, 3 and 4 in parallel
Viewed from active filter	Branch 1 only Branch 1 and 2 in parallel Branches 1, 2 and 3 in parallel Branches 1, 2, 3 and 4 in parallel
Viewed from Node 4	No parallel branch Branch 2 in parallel Branches 2 and 3 in parallel Branches 1, 2 and 3 in

with the conditions that all current source type of loads/DGs are open circuited and all voltage source type of loads/DGs are short-circuited. The ac supply system is assumed as a voltage source. A linear relation between the inductance and frequency is also assumed. To illustrate the effects of line length on the impedance characteristics, another set of line parameters for shorter electrical distance (1/5 of Z_{L1}, Z_{L2}, Z_{L3} and Z_{L4} given above) is also used to generate a group of impedance characteristics for comparative studies.

B. Impedance Characteristics

Various possible operation modes (circuit configurations) are studied. The circuit configurations presented in the paper are given in Table II.

1) Impedance Characteristics Viewed From the Current Harmonic Source: The impedance characteristics viewed from node 1 (excluding PF1) are plotted in Figs. 7 and 8 respectively for the two sets of line parameters in different circuit configurations. The characteristic of the passive filter, PF_1, is also plotted for comparison. Comparing the system impedance characteristics viewed from node 1 with that of the shunt passive filter at node 1, PF_1, in Fig. 7, it can be seen that the passive filter can present lower impedance path in the required frequency range and therefore provide effective filtering. For the case of shorter lines shown in Fig. 8, it can be seen that the impedance characteristics viewed from node 1 become lower due to the reduction of the series impedance in the line circuit.

In the studied case, the passive filter still has lower impedance in the designed frequency range. However, it can be expected, if more parallel branches are added into the system, the passive filter's effectiveness will be suffered, then a redesign of the filter or using one passive filter for a group of closely located loads/DG units may be considered.

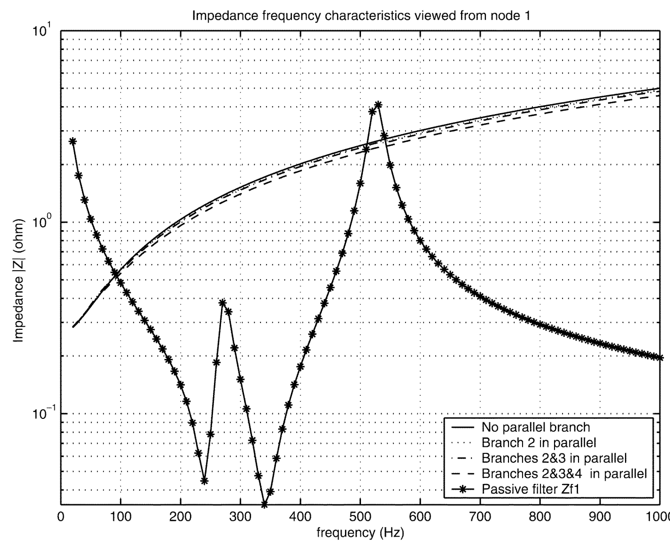

Fig. 7. Impedance characteristics viewed from node 1 in Fig. 6.

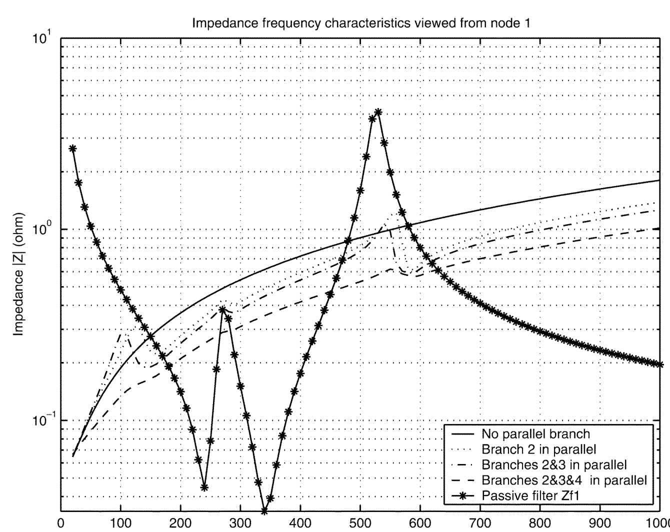

Fig. 8. Impedance characteristics viewed from node 1 in Fig. 6 (shorter electrical distance).

2) Impedance Characteristics Viewed From the Active Filter: The load side impedance characteristics viewed from the active filter are plotted in Figs. 9 and 10 respectively for two sets of line parameters in different circuit configurations. The impedance of the grid supply side is also plotted. It can clearly be seen that the load side equivalent impedance viewed from the active filter is reduced due to the parallel connection

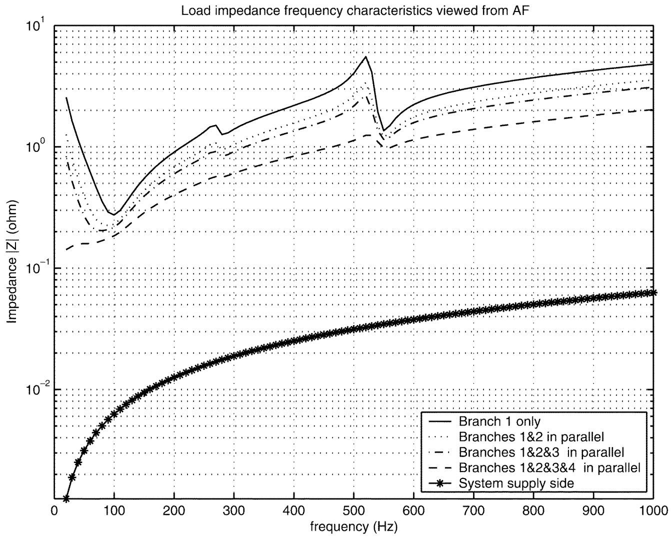

Fig. 9. Load impedance characteristics viewed from the active filter in Fig. 6.

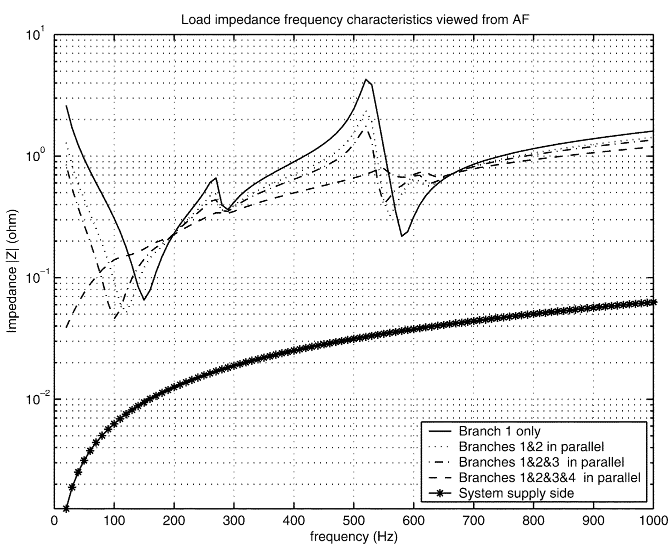

Fig. 10. Load impedance characteristics viewed from the active filter (shorter electrical distance) in Fig. 6.

of loads/DGs and their associated passive filters, especially in the shorter line cases. For the studied case, low impedance appears at around 100 Hz, due to the cancellation of the line impedance with the capacitive admittance of the passive filters in that frequency range. In the shorter line case, the impedance characteristics are further reduced and the low impedance point moves toward higher frequency.

3) Impedance Characteristics Viewed From the Voltage Harmonic Source: The system impedance characteristics viewed from node 4 in Fig. 5, where the voltage harmonic source is located, are plotted in Figs. 11 and 12 respectively for the two sets of line parameters in different circuit configurations. In Fig. 11, it can be seen that the impedance characteristic is mainly dominated by the line impedance, Z_{L4}. Fig. 12 shows the impedance characteristics with shorter electrical distances. It can be seen that the impedance viewed from node 4 is varied due to the connection of other branches and passive filters. This may result in an increase in the harmonic current from the voltage harmonic source at node 4.

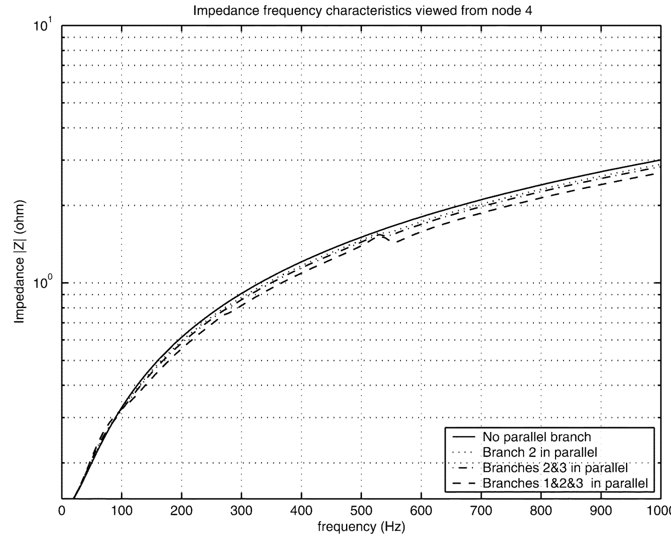

Fig. 11. Impedance characteristics viewed from node 4 in Fig. 6.

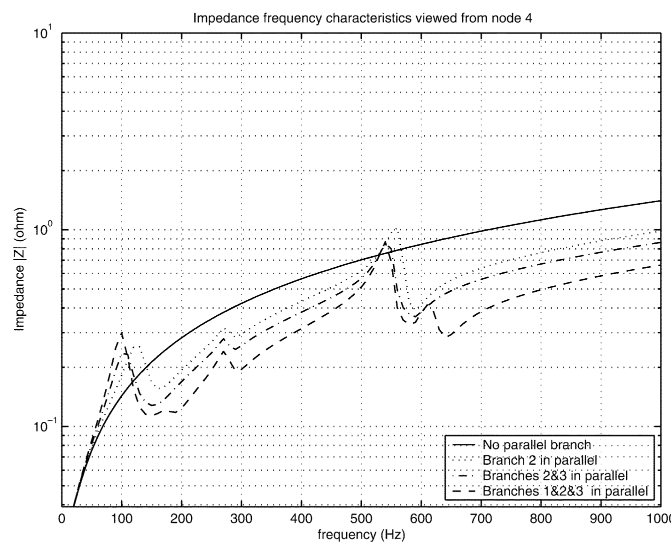

Fig. 12. Impedance characteristics viewed from node 4 in Fig. 6 (shorter electrical distance).

V. Simulation Studies

Comprehensive simulation studies have been performed with PSCAD/EMTDC software package on the system illustrated in Fig. 6. A sinusoidal grid voltage is assumed. Various operation conditions have been studied. Some typical cases are presented in this section. The uncompensated load current waveforms are shown in Fig. 13.

The waveforms of the current in the line branches (after the passive filters) are shown in Fig. 14 under the condition of all loads/DG units in operation. The current waveform of Load 4, which is a voltage harmonic source, is not changed since there is no shunt passive filter. Comparing the waveforms in Figs. 13 and 14, the effects of the passive filters can be clearly seen. Though the current unbalance of Load 2 can be still seen clearly.

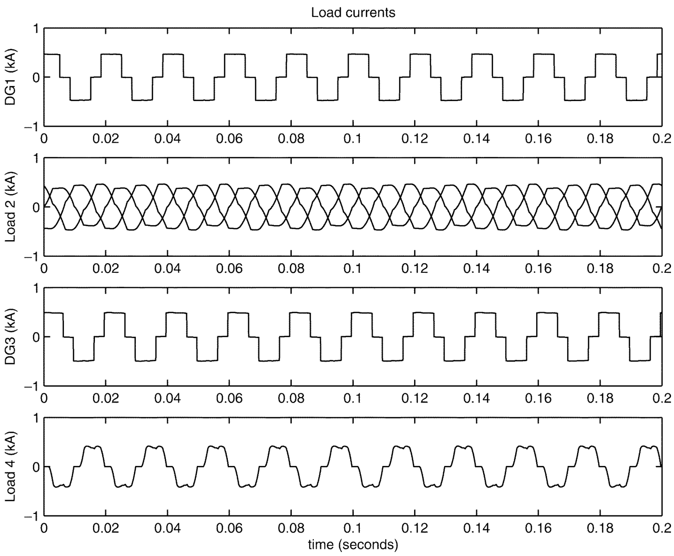

Fig. 13. Current waveforms of DG units and loads.

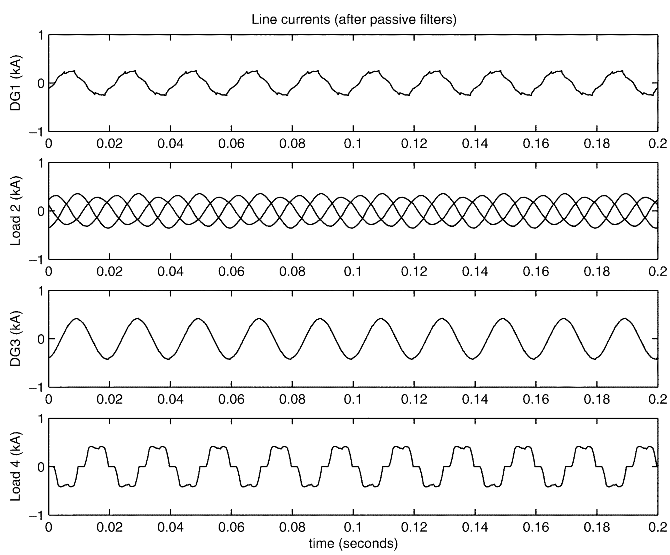

Fig. 14. Current waveforms in line branches (after passive filters).

In the following presented results of current waveforms, the active filter is switched in operation at 0.1 seconds, so that the effect of the active filter can be clearly seen by comparing the system current waveforms before and after 0.1 seconds.

A. All DG Units and Loads With Associated Filters in Operation

Fig. 15 presents the waveforms of the currents entering the system and the current injected by the active filter under the condition of all DG units and loads with associated filters in operation. Before the active filter is switched in, the system current contains harmonics and is unbalanced. It can be seen clearly that the active filter is effective in correcting the distortion.

B. Only Load 4 (The Capacitive Loaded Three Phase Rectifier) in Operation

Fig. 16 presents the waveforms of the currents entering the system and the current injected by the active filter when only

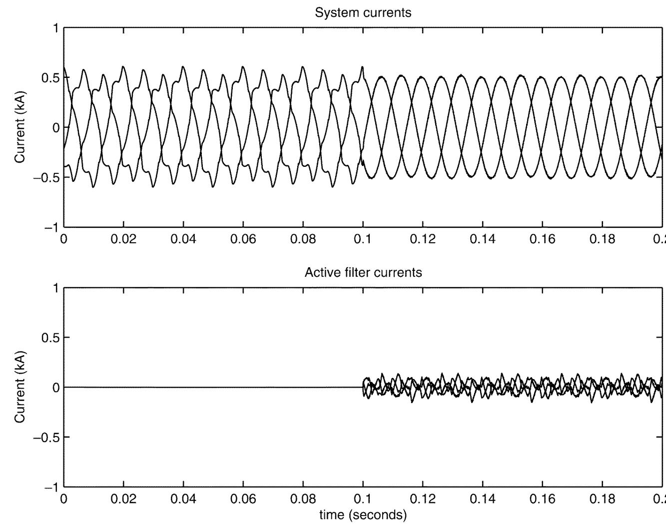

Fig. 15. System and active filter current waveforms (all DG units and loads with associated filters in operation).

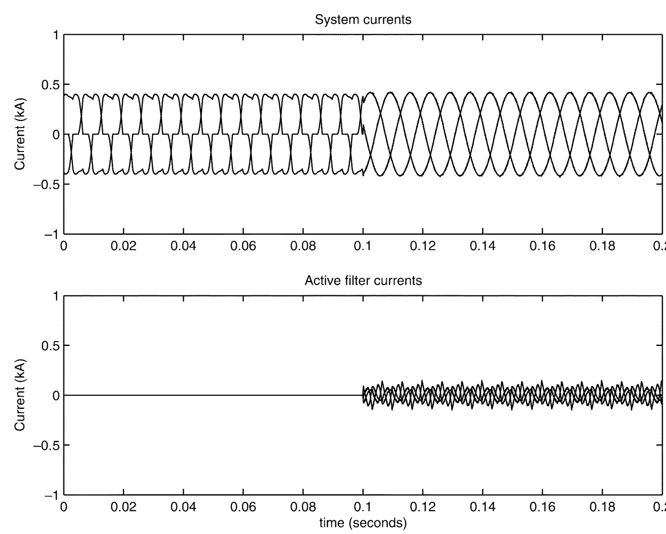

Fig. 16. System and active filter current waveforms (only load 4 *in operation*).

Load 4 (capacitive loaded three phase rectifier) is in operation. It can be seen that the active filter effectively corrects the current waveform into a sinusoidal waveform.

C. All DG Units and Loads in Operation Without Passive Filters

Fig. 17 presents the waveforms of the currents entering the system and the current injected by the active filter under the condition of all DG units and loads in operation but none of the passive filters are in operation. It can be seen that the harmonic and unbalance have been corrected. The active filter is controlled to compensate harmonics and unbalance only, the reactive power is not compensated. Consequently the supply current is increased in comparison with the case that passive filters are in operation as shown in Fig. 15, since there is no passive filter to provide reactive power in the case of Fig. 17.

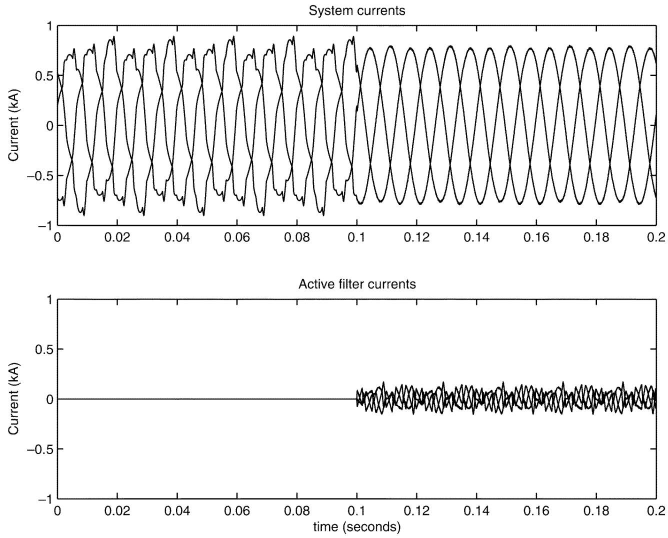

Fig. 17. System and active filter current waveforms (all DG units and loads in operation without passive filters).

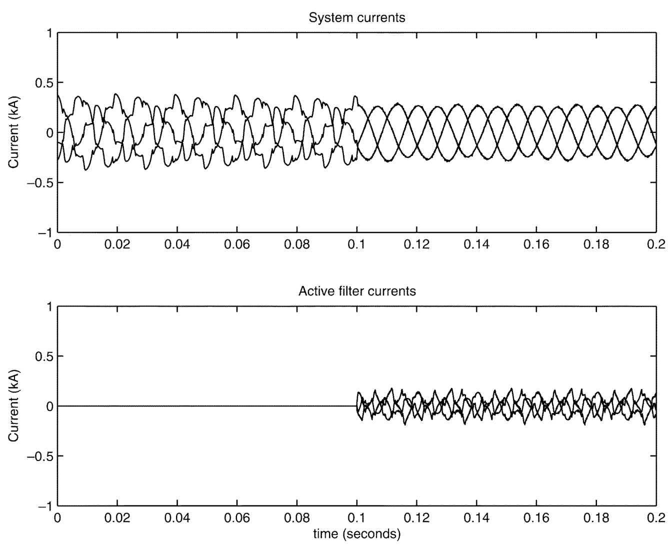

Fig. 18. System and active filter current waveforms (all four branch in operation, short electrical distance).

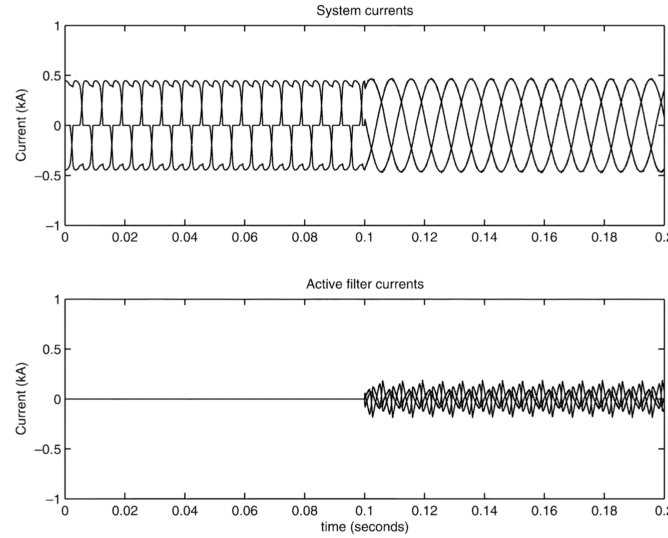

Fig. 19. System and active filter current waveforms (only load 4 in operation, short electrical distance).

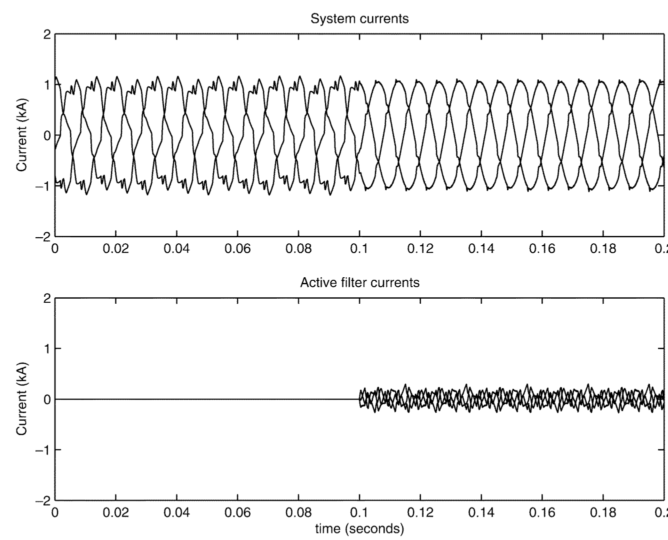

Fig. 20. System and active filter current waveforms (all four branch in operation without passive filters, short electrical distance).

D. All DG Units and Loads With Associated Filters in Operation (Short Electrical Distance)

Fig. 18 presents the waveforms of the currents entering the system and the current injected by the active filter under the condition of all DG units and loads with associated filters in operation in the system with the shorter electrical distance discussed above. The active filter can still correct the waveforms into a sinusoidal shape in this case.

E. Only Load 4 (Capacitive Loaded Three Phase Rectifier) in Operation (Short Electrical Distance)

Fig. 19 presents the waveforms of the currents entering the system and the current injected by the active filter when only Load 4 (capacitive loaded three phase rectifier) is in operation. It can be seen that the active filter is still effective, since there are some impedance exists between the active filter and Load 4. However the low line impedance results in high current from Load 4, which requires a higher active compensation current.

F. All DG Units and Loads in Operation Without Passive Filters (Short Electrical Distance)

Fig. 20 presents the waveforms of the currents entering the system and the current injected by the active filter under the condition that all DG units and loads are in operation without any passive filters for the case of the shorter electrical distance, it can be seen that the unbalance has been corrected but the waveforms still contain harmonics because passive filters are not in operation and more branches are connected in parallel, this increases the harmonic current and reduces the load side equivalent impedance and makes the filtering task more difficult.

VI. DISCUSSIONS

The analysis and simulation show that the hybrid and distributed filtering system can effectively compensate the distorted waveforms.

The compensation effectiveness of the parallel filters is related to the system parameters. An analysis of the impedance characteristics can provide good indication on determining the filtering system arrangement. Various possible system configurations should be considered to ensure that the filter system perform appropriately under all possible operation conditions.

As predicted by the impedance characteristic analysis, the simulation results show that the presented hybrid compensation system can perform well in harmonic and system unbalance correction under the studied conditions.

The distributed passive filters can solve the reactive power and major harmonics locally, however, if the loads/DGs are located closely (very short electrical distance), care should be taken to design these passive filters, one passive filter may be better suited for a group of closely connected loads/DGs.

The results also show that the active filter without the assistance of passive filters may have difficult to remove all the harmonics in the studied shorter electrical distance case.

VII. CONCLUSIONS

The paper extends the concept of connecting one active filter and one passive filter in parallel into a hybrid compensation system consisting of an active filter and a group of distributed passive filters. Passive filters are used for each distorting load/DG to remove major harmonics and provide reactive power compensation. The active filter is connected in parallel with the distributed passive filters and loads/DGs to correct the system unbalance and remove the remaining harmonic components. The effectiveness of the presented compensation system has been demonstrated. The system may be used for a local network, a DG system, a wind farm, etc.

The variations of system impedance characteristics caused by the connection of multiple loads and passive filters have been analyzed and the effects on the compensation system have been discussed.

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