2005 IEEE Electric Ship Technologies Symposium

Parallel Operation of Shunt Active Power Filters for Damping of Harmonic Propagation in Electric Shipboard Power Systems

Ting Qian[1], Brad Lehman[1], Anindita Bhattacharya[1], Herb Ginn[2], Marshall Molen[2]
1. Northeastern University 2. Mississippi State University

Abstract: For modern navy electric ship, the application of multiple shunt active power filters (SAPF) has become an attractive choice to mitigate the current distortion of the nonlinear loads. Multiple SAPF has the advantage of high power capacity and high reliability. Based on the introduction of SAPF, this paper analyzes the importance of paralleling SAPF in electric ship systems. A new paralleling approach is proposed and compared with several known paralleling/cascading methods. The proposed method separates the tasks of compensating for reactive power and harmonic currents. It has fast response and is suitable for redundancy design. Simulation results verify the analyses.

I. Introduction

The use of nonlinear loads such as power electronic devices in power distribution systems has recently become prevailing. For example, a modern day navy electric ship uses large number of power electronic based devices for the speed control of its propulsion system, accurate control of its combat systems, ship system automation and electrification of loads. Future navy systems, such as electromagnetic aircraft launch systems, laser weapon systems and advanced pulsed power weapons, will also require power electronic systems to control and manage shipboard energy. An important technical challenge when implementing these power electronic devices is that they do not draw purely sinusoidal currents, and instead draw distorted currents. These currents create harmonic distortion in the electrical current and voltage waveforms of the power system. Furthermore, the loads often have a low power factor, and there is a significant deterioration of power quality in the electrical plants of modern warships.

Several problems can arise with the harmonic distortion:

- False tripping of the protective devices;
- Extra heating losses in motors, transformers and cables;
- Less accurate measurements of the sensors;
- Mechanical vibration and noise;
- Possible computer network failures;
- System resonance at harmonic frequencies. [1]

A popular method to mitigate the harmonics problem in any power distribution system is to use passive filtering based on resonant filters or high pass filters. These filters are inexpensive and highly efficient. But passive filters have several drawbacks, such as variation of filtering characteristics with source impedance, as well as the risk of anti-resonance between the line impedance and the resonant circuit [2]. Passive filters are tuned most of the time on a particular harmonic to be eliminated and if better results are needed, multiple passive filters are utilized [3]. In the electric ship, where the loads are always changing and the frequencies of harmonic disturbances are often unknown, it would be difficult to tune passive filters. Furthermore, the weight and volume of the passive components, such as their capacitors and inductors, become significant for high power system, such as in an electric ship.

Thus, an alternative approach is to use a Shunt Active Power Filter (SAPF). A SAPF is considered to be a current source connected in parallel with the nonlinear load [4]. It suppresses the harmonic currents created by the non-linear loads by injecting an appropriate current of the same amplitude and reverse phase to that of the load current harmonics.

This paper proposes to introduce multiple Shunt Active Power Filters (SAPFs) on an electric ship. We suggest that there are improved advantages to consider multiple SAPF on the electric ship, particularly since SAPFs can be easily paralleled. We propose a new method to operate the SAPFs, delegating different job duties to each one according to their locations. In summary, the results of this paper are:

- *Different existing paralleling methods for shunt SAPFs are described. Specific technical issues, such as response during step load change and power capacity, are discussed.*
- *A new paralleling method is proposed. The advantages of the method for ship electrical systems are explained.*

0-7803-9259-0/05/$20.00 ©2005 IEEE.

- *The simulation results for multi-SAPFs are applied to support the analysis.*

II. Principle of operation of a Shunt Active Power Filter

As stated earlier, a SAPF is connected in parallel with the nonlinear load. It works as a current source and suppresses the harmonic currents by injecting an appropriate current of the same amplitude and reverse phase to that of the load current harmonics. The SAPF can also compensate the load power factor with the appropriate control scheme. Fig. 1 shows the principle of operation of a shunt active power filter. The SAPF consists of three different parts – the reference current generator, the control circuit and the Voltage Source Inverter. The reference current generator detects the current and source voltage and using Instantaneous Reactive Power based theory (PQ theory) [2] or the Synchronous Reference Frame based control [5], it creates the reference current. The reference current then goes through the control circuit and creates the control signal. The control signal is then sent to the Voltage Source Inverter (VSI) and the VSI injects the appropriate compensating current to the power system. The structure of the Voltage Source Inverter is shown in Fig. 11 in the appendix. Most of the Voltage Source Inverters use an energy storage device, usually a capacitor at the DC bus. Then with the use of power semiconductor switches and pulse-width-modulation technique, it converts the DC voltage into AC voltage [6]. At the output of the PWM voltage source inverter, inductances are used to limit the level of the ripple current [3].

III. Ship system and importance of paralleling

Contemporary US Navy ships are designed with different categories of loads, named particularly vital, vital and non-vital loads [7]. Particularly vital loads are the most important ones and are connected with automatic bus transfer switches to provide power even after failure of the primary source. Vital loads are less important than particularly vital loads and connected with a manual bus transfer switch. Non-vital loads are the least important ones and do not need to provide any transfer switch. According to prioritization, loads in the naval ships continuously change. At the time of war, the main priority of the ship is to use the weapons. If it is being attacked by the enemy, the main priority is self-defense of the ship, and at the time of peace, mainly the electrification and ventilation gets the highest priority. Thus, unlike the terrestrial power system, the load characteristic changes in Naval ship power systems. Therefore, we need a structure which can help the shunt active power filters to respond according to the changes of the loads.

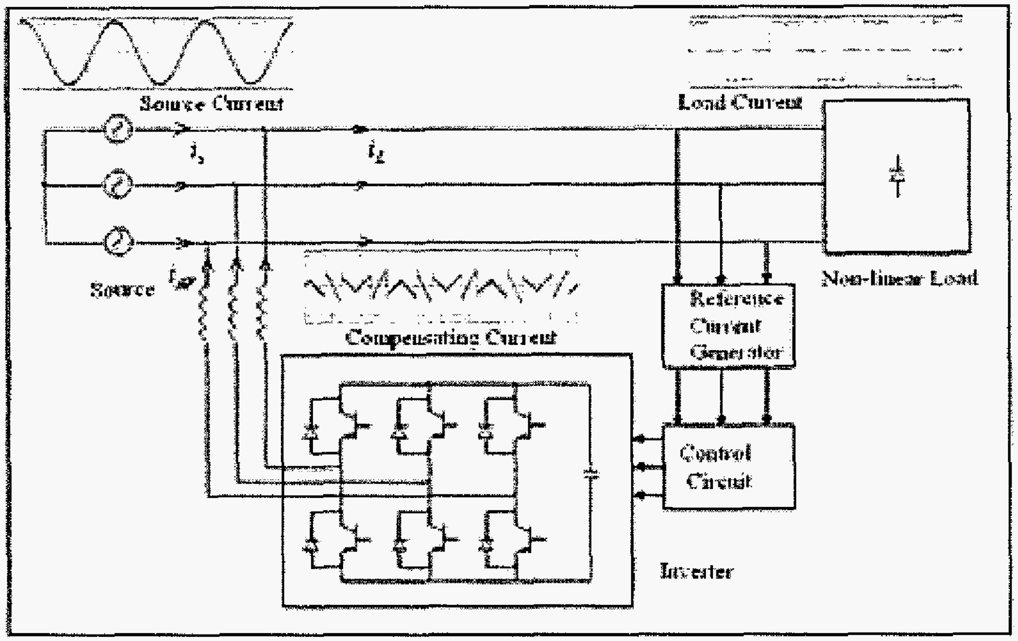


Fig. 1 Principle of operation of a shunt active power filter

However, when evaluating the use of SAPF's on a naval ship, several technical issues should be addressed. Firstly, the naval electric system contains several high power loads and generators. Therefore, any proposed compensation scheme must have high power capacity. This leads to the natural evolution of using multiple SAPFs in parallel. However, not all SAPF paralleling/cascading methods have equally distributed additive power capacities. Sometimes individual SAPFs are made with smaller power capacity compared to others-in order to quicken transient response. Thus, when selecting a paralleling SAPF method for a navy ship, power capacity must be carefully considered.

Similarly, reliability is also a major concern for an electric ship. When a primary APF fails to act properly, it must be swapped with a backup APF while maintaining connectivity to the system with little or no impact on the system at all. Some paralleling SAPF methods have inherent redundancy in their designs, while others do not [8]. Another design criteria that should be considered is speed of response of the paralleled SAPFs. This is directly related to each APF's inductor size (slew rate) and controller response speed. In navy ship, power system architectures that are "reconfigured" loads suddenly appear, disappear, become vital, etc. Quick harmonic mitigation should occur in order to minimize the detrimental effects of these sudden changes. This may imply that load sharing approaches requiring communication between the SAPFs might not be desirable due to communication latencies. Instead an independent control approach for each individual may be quicker, and, in fact, may have better redundancy.

In the following section, we evaluate known approaches, and a newly proposed approach, to operating SAPFs in parallel in terms of these above design criteria.

IV. Existing paralleling methods

[A] Cascaded current sensing with same APFs [9]:

This paralleling method employs a cascaded current sensing system. Capacity limitation setting is based on the APF specification. In this scheme, one capacity limited APF can only compensate the distortion left by the other APFs connected on the downstream. If it can not handle all the compensation, it will leave the remaining distortion to the other capacity limited upstream APFs. There is no control interconnection among APFs. Assume in Fig.2 that each of the N cascaded APFs is the same. Each APF provides limited reactive power and injects harmonic currents with limited amplitude. The characteristic is that the input current of the (i-1)th APF is the same as the load current of the ith APF (i=2,3,...,N). As a result, the ith APF will treat the APFs on its load side (i.e. from the 1st APF to the (i-1)th APF as one part of its load [9]. Because the controller of each APF is independent for this cascading method, failure of one APF will not impact the operation of the other APFs. Thus, on-line replacement and maintenance of the APFs is also possible. These features make the design suitable for redundancy consideration. One disadvantage of the cascading approach is the slow response during load change. Since the upstream APFs sense the current after the compensation of the downstream APFs, the time that they need to reach steady state during load change will be influenced by the delay of the downstream APFs.

[B] Parallel APFs for different frequency harmonics [10]:

In this paralleling method shown in Fig.3, two APFs are used to compensate for the current harmonics and reactive power. Each PWM voltage-source inverter operates with different switching frequency allowing the generation of specific current harmonic component of the nonlinear load [10]. The downstream APF, which is connected closer to the nonlinear load, operates at a lower switching frequency. It compensates for the displacement power factor and the low-frequency current components generated by the nonlinear load. It can be implemented with Gate Turn Off switches to provide larger rms currents. Therefore, the size of the filter, including the size of the power inductor, is large. On the other hand, the upstream APF operates at a higher switching frequency and compensates for only the high

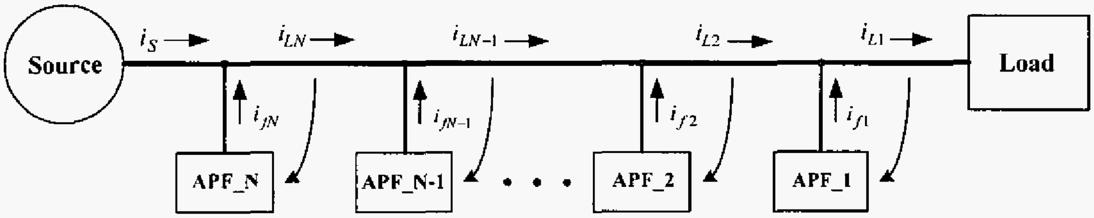


Fig. 2 Normal cascading method (One phase shown)

frequency current components. Bipolar transistors or insulted gate bipolar transistors can be used in this case to generate lower rms current. This upstream APF has the fast switching capability and lower capacity. The size of the APF is much smaller when compared with the downstream one. Further, because each APF is designed for different purposes, their power capacities differ. There is limited redundancy since neither APF can perform each other's job.

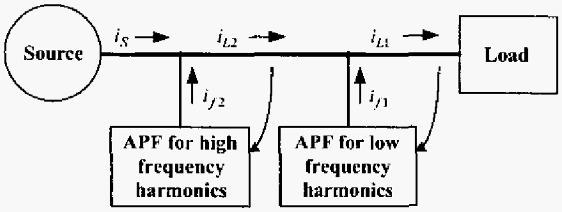


Fig.3. Parallel APFs for different frequency harmonics

V. Proposed paralleling method

Figure 4 shows the proposed paralleling method. The APFs are connected in cascade while the tasks of compensating for reactive power and harmonic currents are separated. APF1 compensates for unwanted harmonics, while APF2 compensates for reactive current. APF2 measures the current after the compensation of APF1. Since most harmonics are compensated for by APF1, APF2 functions mainly for fundamental component of the reactive current.

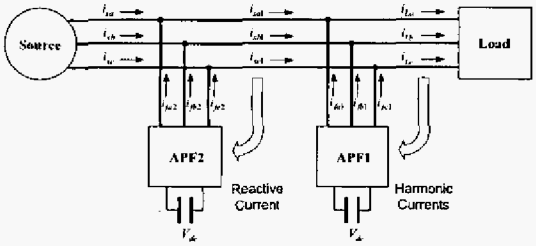


Fig. 4 Compensate for harmonics and reactive power separately

As the task of two different APFs are different, their control block diagrams are also different. Fig. 5 shows the control block diagram of the APF1. This APF deals with only the unwanted harmonics. Two low pass filters have been used to get rid of the fundamental part of the active and reactive power. APF2 deals with only the reactive power. As shown in Fig. 6, this APF does not have any low pass filter, but it deals with only the fundamental part of the reactive power. Unlike paralleling APFs for different frequency harmonics, the proposed method keeps the high power capacity of both APFs. The new algorithm can also be expanded to enlarge the power capacity when applying a group of APFs in the distributed ship system.

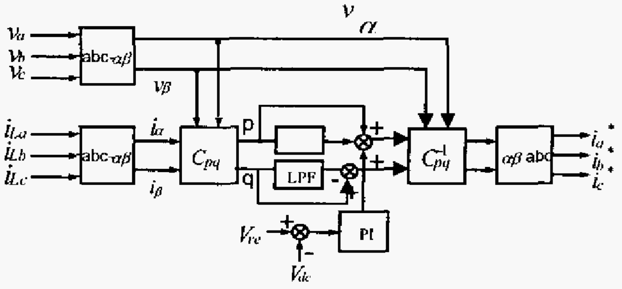


Fig. 5. Control Block diagram of APF1

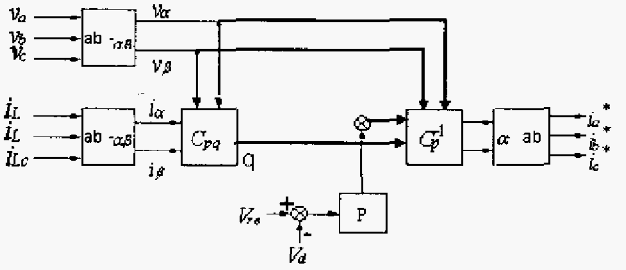


Fig. 6. Control Block diagram of APF2

Comparing with the existing methods based on the difference of ship system and normal power system, the proposed multi-APF strategy has the following advantages:

- *The new method makes it simpler to apply standard APF models in the ship power system.* When a group of APFs are connected within the ship power distributed system, the different locations/buses have distinct power quality preferences with delivery to loads with different load priorities. Therefore, the tasks for different APFs need to be classified differently. Clearly separating the suggested two kinds of compensation makes it easier to determine: the numbers, the power ratings, and the locations of the SAPFs
- *Flexible choice for inductor design according to different requirements for current response can be achieved.* The fundamental component of the reactive current changes slowly, while harmonic currents change quickly. Therefore, the APFs are able to utilize suitable inductance value based on their own specific demands.
- *Fast response can be achieved.* The reference generator of APF2 has quick response because it does not require a low pass filter to obtain the mean value of instantaneous reactive power. Since the delay of reference generator and voltage loop of APF1 is related with active power, it has no effect on APF2.

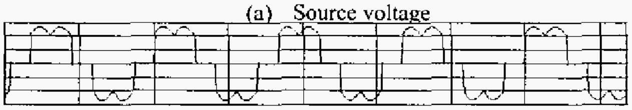
Comparison of different paralleling methods

Type	Description	Response	Power capacity	Redundancy design
1. Cascaded current sensing with same APFs	Same APFs are utilized. Reactive power and amplitude of harmonics are limited.	Slow	Both APFs can handle high power.	Suitable for redundancy design
2. Paralleling according to frequency	APF1 for low frequency and APF2 for high frequency harmonics.	Fast	Only the APF in charge of low frequency can handle high power.	Not suitable.
3. Paralleling according to different types of compensation (proposed method)	APF1 only for harmonics and APF2 only for reactive power.	Fast	Both APFs can handle high power.	Suitable when the control goal can swap between APFs.

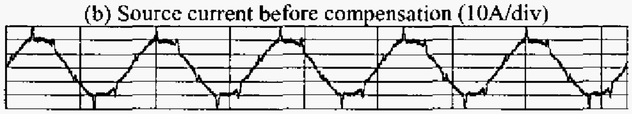
Table 1. Comparison between two known multiple SAPF schemes and the new proposed approach.

VI. Simulation results

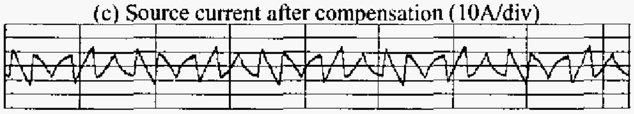
(a) Source voltage



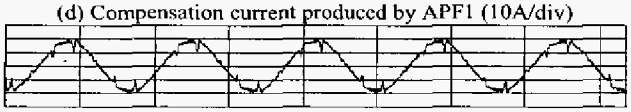
(b) Source current before compensation (10A/div)



(c) Source current after compensation (10A/div)



(d) Compensation current produced by APF1 (10A/div)

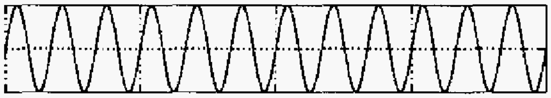


(e) Compensation current produced by APF2 (10A/div)

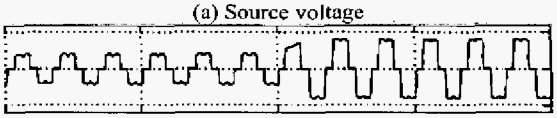
Fig.7 Simulation results of the proposed paralleling approach

Fig.7 shows the simulation results of the proposed paralleling approach. From the waveforms it can be seen that the harmonics and reactive power is greatly suppressed by the two paralleled APFs. Even though it is possible to achieve this result using a single SAPF in a power system, the paralleling gives us much more flexibility and reliability. Fig.7(d) shows the output current of the downstream APF1. From the waveform, most of the unexpected harmonics are compensated for. Fig.7(e) shows the current generated by the upstream APF2 to compensate for the remaining distortion. From the waveform, APF2 mainly handles the fundamental component of the reactive power. By doing this, the source current is near sinusoidal and unity power factor is obtained. Fig.7(c) supported the effectiveness of the proposed paralleling approach.

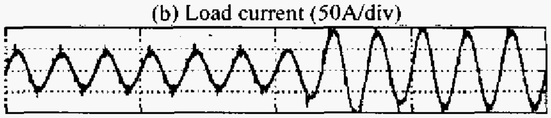
To further understand the performance of different paralleling methods for SAPFs, Figs. 8-10 compare the results in another simulation experiment. In these simulations, two APFs are paralleled for each kind of method. The response of the paralleled APFs during step load change can be seen from the waveforms. According to the above analysis and simulation results, the conclusions in Table.1 are obtained.



(a) Source voltage



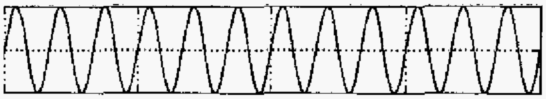
(b) Load current (50A/div)



(c) Source current of type1 (20A/div)

Fig.8 Simulation results of Type I paralleling method

Type1 (cascaded current sensing with same APFs) has good compensating performance. Since both APFs can handle high power, this method is suitable for redundancy design. As Fig. 8 indicates, the primary disadvantage is that the response is slow during step load change. Notice in Fig. 8 that it takes about three line cycles to reach steady state during step load change because the latency of downstream APF influences the time that the upstream APF needs to reach steady state.


(a) Source voltage


(b) Load current (50A/div)

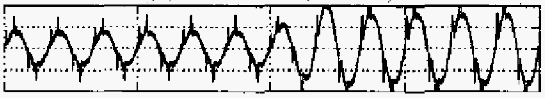
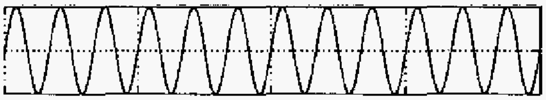
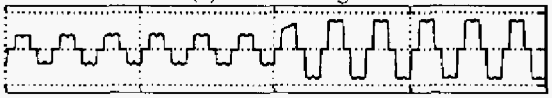

(d) Source current of type2 (20A/div)

Fig.9 Simulation results of Type 2 paralleling method

Fig. 9 shows that Type2 paralleling method (paralleling according to frequency) has the benefit of faster response. For Type2, only the APF in charge of low frequency handles high power. The design is not suitable for redundancy consideration. The response is still fast since it needs only one and a half line cycle to reach steady state.


(a) Source voltage


(b) Load current (50A/div)

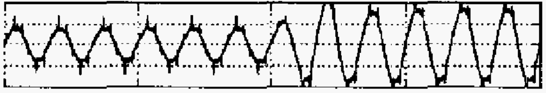

(c) Source current of type 3 (20A/div)

Fig.10 Simulation results of Type 3 paralleling method

Overall, Type3 (proposed method) has flexible power design and fast response. Like Type2, this method is able to reach steady state in about one and a half line cycle during step load. The waveforms are shown in Fig.10. Also, both APFs can handle high power. This feature is suitable for redundancy design. Based on the above analysis and simulation results, the features of the three different types of paralleling methods are compared in Table.1.

VII. Conclusion

The application of SAPF is becoming more popular to mitigate harmonic distortion. However, there is limited research on how to properly operate shunt APFs in parallel. This research proposes a suitable solution for paralleling multiple shunt APFs with specific application to the navy electric ship. Unlike terrestrial power systems, US Navy ships have special characteristics and design requirements, such as continuous changes of load, high power handling needs, reliability, etc. The proposed SAPF paralleling method can respond fast with the load changes since both the APFs can handle high power. Redundancy design is also simple, making it suitable for naval applications.

References

[1] Hegazy Y.G., Salama M.M.A., "Identifying the relationship between voltage harmonic distortion and the load of harmonic producing devices in distribution networks," *Electrical and Computer Engineering, Conference Proceedings*, Canadian Conference, on 25-28 Sept. 1994, vol.2, pp:669 – 672.

[2] Akagi H., "Trends in active power line conditioners," *Power Electronics, IEEE Transactions on* Vol.9, Issue 3, May 1994, pp:263 – 268.

[3] Le Magoarou F., Monteil F., "Influence of the load on the design process of an active power filter," *Industrial Electronics, Control and Instrumentation, 1994*, Vol. 1, 5-9 Sept. 1994, pp:416 – 421.

[4] Rudnick H., Dixon J., Moran L., "Delivering clean and pure power," *Power and Energy Magazine, IEEE*, Vol.1, Issue 5, Sep-Oct 2003, pp:32 – 40.

[5] Marques G.D., "A comparison of active power filter control methods in unbalanced and non sinusoidal conditions," *Industrial Electronics Society, 1998*. Vol.1, 31 Aug.-4 Sept. 1998, pp:444 – 449.

[6] Moran L., Godoy P., Wallace R., Dixon J., "A new current control strategy for active power filters using three PWM voltage source inverters," *Power Electronics Specialists Conference, 1993*, 20-24 June 1993, pp:3 – 9.

[7] Amy, J.V., Jr., "Considerations in the design of naval electric power systems," *Power Engineering Society Summer Meeting, 2002*, vol.1, 21-25 July 2002, pp:331 – 335.

[8] Chiang S.J., Chang J.M., "Design and implementation of the parallelable active power filter," *Power Electronics Specialists Conference, 1999*, vol.1, 27 June-1 July 1999, pp:406 – 411.

[9] Chiang S.J., Ai, W.J., "Parallel operation of three-phase four-wire active power filters without control interconnection," *Power Electronics Specialists Conference, 2002*, vol.3, pp.1202 – 1207.

[10] Moran L.A., Fernandez L., Dixon J.W., Wallace R., "A simple and low-cost control strategy for active power filters connected in cascade," *IEEE Transactions on Industrial Electronics*, Vol.44, No.5, pp:621-629, Oct 1997.

[11] L.Malesani, L. Rossetto y P. Tenti, 'Active Filters for Reactive Power and Harmonic Compensation', *Proceedings of the IEEE-PESC*, Junio 1986, pp 321-330

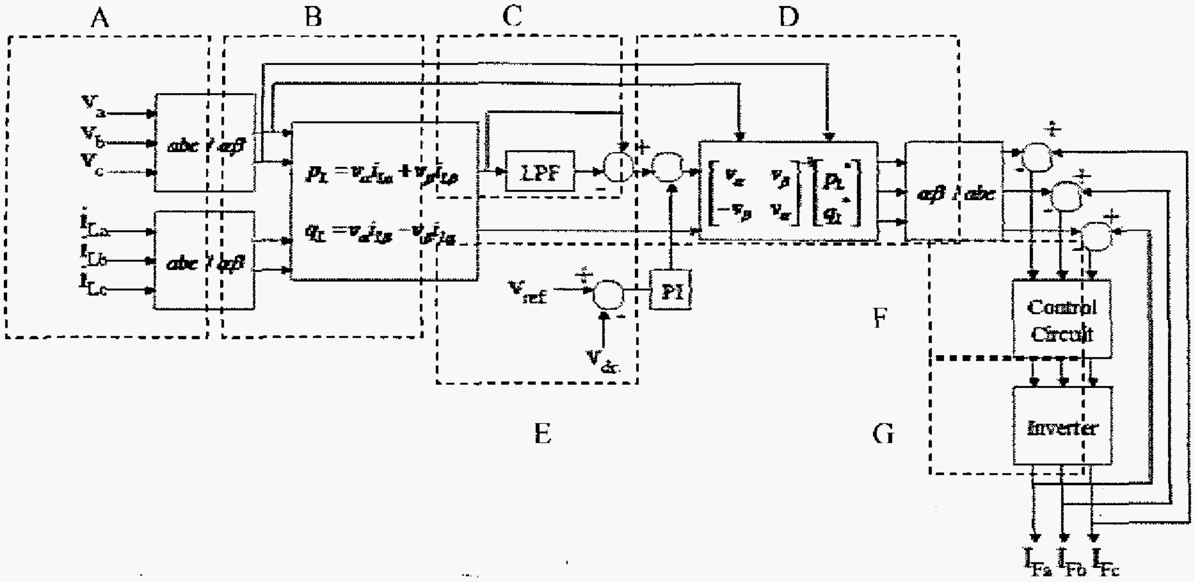


Fig.11. Construction of SAPF with Instantaneous Reactive Power Based control reference generation.

APPENDIX

A. Instantaneous Reference Theory

Fig. 11 shows the detailed structure of the Instantaneous Reference Theory based reference generator and the other two parts of the SAPF.

Fig. 11 shows the conventional IRP based control for APF [2].

Transformation of the three-phase voltages v_a, v_b and v_c and the three- phase load currents i_{La} , i_{Lb} and i_{Lc} and into the $\alpha - \beta$ orthogonal coordinates give the following expressions:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (1)$$

Where x denotes line current or voltage.

In the first block of Fig. 11, named A, the source voltage and the line current are transformed into the $\alpha - \beta$ orthogonal coordinates using (1).

According to the p-q theory, the instantaneous real power p_L and the instantaneous imaginary power q_L are defined as $p_L = v_\alpha i_{L\alpha} + v_\beta i_{L\beta}$ and $q_L = v_\alpha i_{L\beta} - v_\beta i_{L\alpha}$. The block named B in Fig. 11. creates the instantaneous real and imaginary power p_L and q_L respectively. In block C, the low pass filter is used to get the fundamental value and later subtract it from the total current to get the harmonic current.

The commands of three-phase compensating currents (i_{ac}^*, i_{bc}^* and i_{cc}^*) injected by the SAPF are given by the following.

$$\begin{bmatrix} i_{ac}^* \\ i_{bc}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_L^* \\ q_L^* \end{bmatrix} \qquad (2)$$

p_L^* : instantaneous real power command

q_L^* : instantaneous imaginary power command

Block D performs the calculations of (2) and creates the reference currents i_{ac}^* , i_{bc}^* and i_{cc}^* . The block F is the control circuit and it creates the control signal for the inverter. The main parts of the control circuit are the PWM and the Proportional Integral circuit. Block G shows the inverter which generates the appropriate compensating current. The basic structure of the VSI is shown in Fig. 11. Block E represents the voltage loop.

B. Synchronous Reference Frame based control

In the synchronous reference frame method, the load current is transformed into the d-q rotating frame [11]. The transformation is defined by

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (3)$$

Here x denotes load voltages or currents.