Operation of Shunt Active Power Filter Under Unbalanced and Distorted Load Conditions

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Abstract

In this study, reduced current measurement control method is investigated for operation of 3-phase 4-wire shunt active power filter (SAPF) under unbalanced and distroted load conditions. The control method is based on Instantaneous Reactive Power theory (IRP) and requires only measuring the source currents to reduce the number of Current Sensors (CSs) needed in the conventional control approach. The control technique has been tested under different load conditions using Matlab/Simulink simulations and validated with a 10kVA/380V experimental prototype based on TMS320F28335 Digital Signal Processor (DSP). Both simulation and experimental test results demonstrate that the viability of the reduced current measurement method, successful in meeting the IEEE 519-1992 recommended harmonic standard limits.

1. Introduction

Harmonic current pollution of three-phase electrical power systems is becoming a serious problem due to the wide use of non-linear loads, such as diode or thyristor rectifiers and a vast variety of power electronics based appliances. Traditionally, passive LC filters have been used to eliminate the current harmonics and to improve the power factor. However, passive LC filters are bulky, load dependent and inflexible. They can also cause resonance problems to the system. In order to solve these problems, APFs have been reported [1-5] and considered as a possible solution for reducing current harmonics and improving the power factor.

Fig. 1 shows the basic compensation principle of the three phase shunt APF. It is designed to be connected in parallel with the non-linear load to detect its harmonic and reactive current and to inject into the system a compensating current. In the conventional p-q theory based control approach for the shunt APF, the compensation current references are generated based on the measurement of load currents. However, the current feedback from the SAPF output is also required and therefore, minimum six CSs are desired in a unbalanced system.

In addition, the reference current calculation algorithm are simplified and easily implemented in the experimental prototype. In the reduced current measurement control algorithm, sensing only three-phase voltages, three source currents and a DC-link voltage is adequate to compute reference currents of the three-phase SAPF. In this way, the overall system design becomes easier to accomplish and the total implementation cost is reduced.

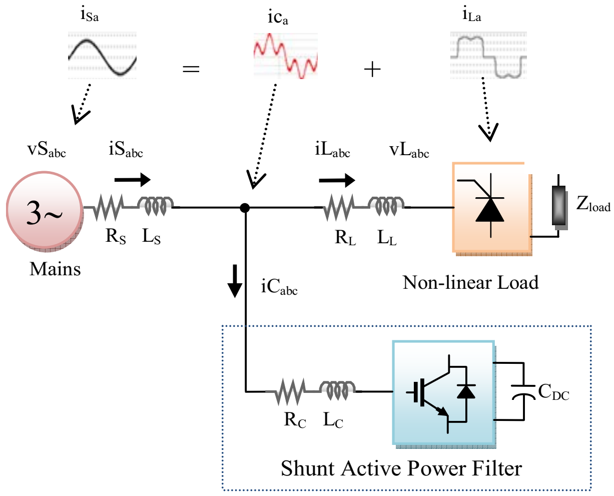

Fig.1. SAPF block diagram

2. Reference Current Signal Generation for Shunt Active Power Filter

The shunt active power filter control algorithm is shown in Fig. 2. Instantaneous reactive power (p-q) theory is used to control of shunt active power filter in real time. In this theory, instantaneous three-phase current and voltages are transformed to α-β-0 from a-b-c coordinates as shown in equation (1) and (2).

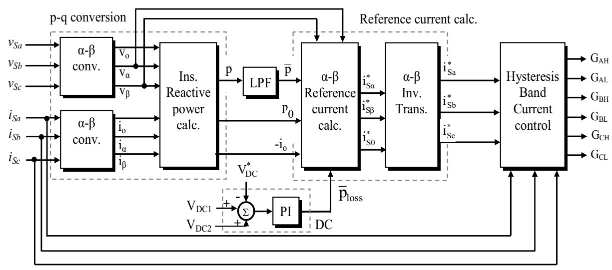

Fig. 2. Shunt active power filter control block diagram.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (2)$$

Load side instantaneous real and imaginary power components are calculated by using source currents and phase-neutral voltages as given in equation (3).

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Instantaneous real and imaginary powers include AC and DC components as shown in (4). DC components of p and q composed from positive sequence components ($\overline{p}$ and $\overline{q}$) of load current. AC components ($\tilde{p}$ and $\tilde{q}$) of p and q include harmonic and and negative sequence components of load currents [4,5].

In order to reduce neutral current, p_0 was calculated by using DC and AC components of imaginary power and AC component of real power; as given in (5) if both harmonic and reactive power compensation is required

$$p_0 = v_0 . i_0 \quad ; \quad p = \overline{p} + \tilde{p} \quad ; \quad q = \overline{q} + \tilde{q} \quad (4)$$

$$\begin{bmatrix} i^*_{S\alpha} \\ i^*_{S\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \overline{p} + p_0 + \overline{p}_{loss} \\ 0 \end{bmatrix} \quad (5)$$

$i^*_{s\alpha}$ and $i^*_{s\beta}$ are reference currents of shunt active power filter in α-β-0 coordinates. To compensate neutral current, $i^*_{s0}=-i_0$ These currents are transformed to three-phase system as shown below in equation (6).

$$\begin{bmatrix} i^*_{Sa} \\ i^*_{Sb} \\ i^*_{Sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i^*_{S0} \\ i^*_{S\alpha} \\ i^*_{S\beta} \end{bmatrix} \quad (6)$$

The reference currents in three-phase system (i^*_{sa} i^*_{sb} ve i^*_{sb}) are calculated in order to compensate neutral, harmonic and reactive currents in the load. The switching signals used in shunt active power filter control algorithm are generated by comparing reference currents and actual line currents and using hysteresis band current control algorithm [6].

3. Simulation Results

In this study, reduced current measurement control method algorithm for SAPF is evaluated by using simulation results given in Matlab/Simulink software. The experimental and simulated SAPF system parameters are given in Table I. In simulation studies, the result are specified before and after SAPF system is operated. In addition, when SAPF system is operated, load has changed and dynamic response of the system was tested. The reduced current measurement control method algorithm has considerably good simulation results as compared the conventional control algorithms.

Table I. SAPF Experimental and Simulation parameters.

	Parameters		Value
Source	Voltage	v_{Sabc}	380 V_{rms}
	Frequency	f	50 Hz
Load	3-Phase AC Line Inductance	L_{Labc}	2 mH
	1-Phase AC Line Inductance	L_{La1}	1 mHΩ
	3-Phase DA Inductance	L_{da3}	10 mH
	3-Phase DA Resistor	R_{da3}	30 Ω
	1-Phase DA Resistor	R_{da1}	87,5 Ω
	1-Phase DA Capacitor	C_{da1}	240 μF
DC Link	Voltage	V_{DA}	700 V
	Capacitor1/2	C_1 C_1	1100 μF
SAPF	AC Line Inductance	L_{Cabc}	3.5 mH
	Filter Resistor	R_{Cabc}	5 Ω
	Filter Capacitor	C_{Cabc}	10 μF
	Switching Frequency	f_{pwm}	~15 KHz

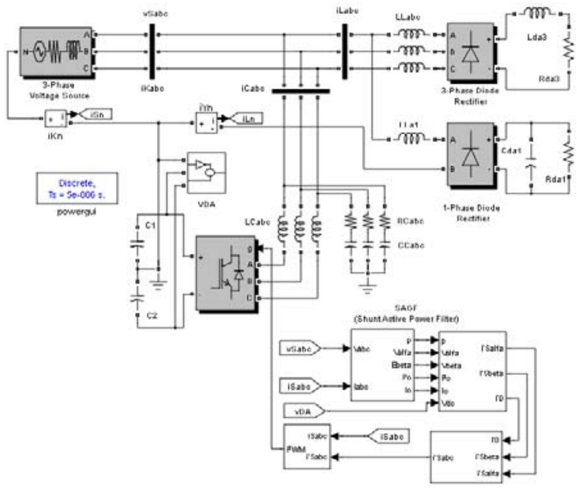

Fig. 3. The SAPF control algorithm block diagram.

Load current compensation simulation results under non-linear (unbalanced-distorted) load current conditions are given in Fig. 4. The neutral current compensation results are given in Fig. 5. Load-mains current and voltage waveforms in phase "a" are shown in Fig. 6. SAPF control algorithm has ability to compensate both harmonics and reactive power of the load and neutral current is also eliminated[4,5].

The reduced current measurement control method algorithm control technique has been evaluated and tested under dynamical and steady-state load conditions Simulation results for under load changing are shown in Fig. 7.

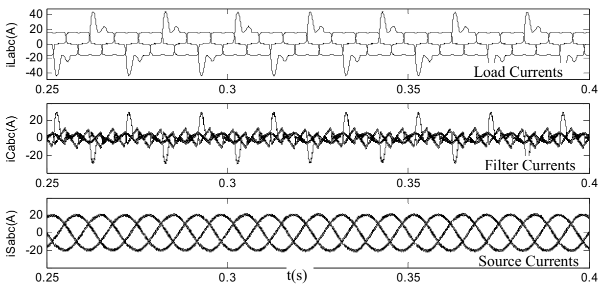

Fig. 4. Simulation results for unbalanced and non-linear load current condition.

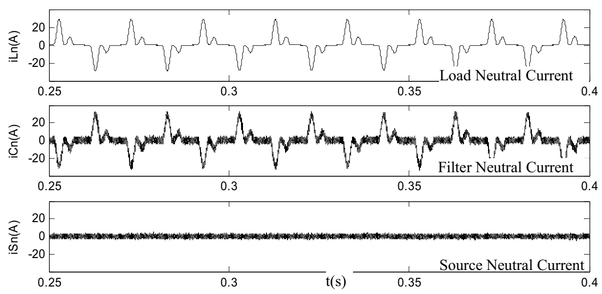

Fig. 5. Simulation results for neutral current and reactive power compensation.

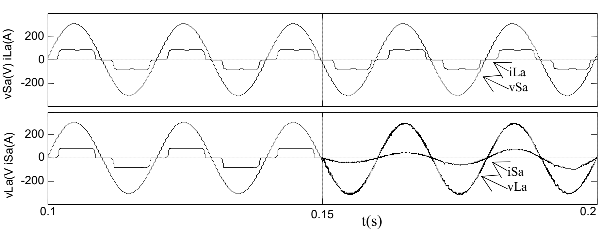

Fig. 6. Simulation results for reactive power compensation.

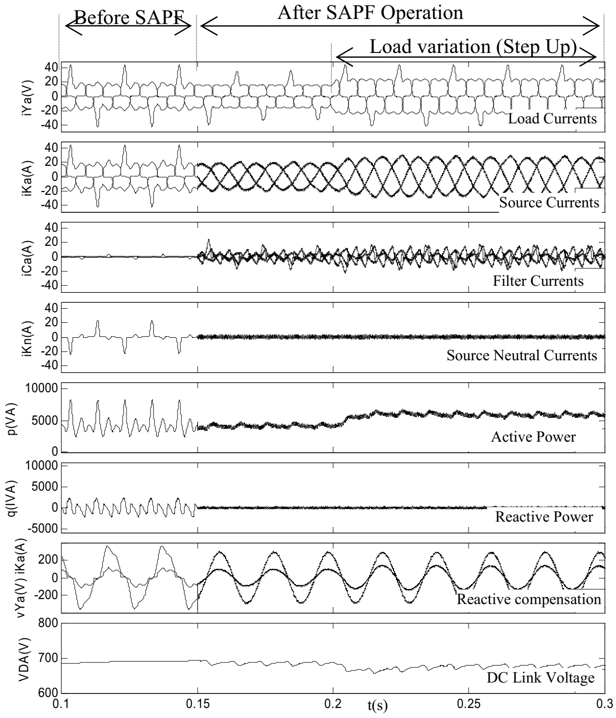

Fig. 7. Simulation results for operation performance of the SAPF system.

4. Experimental results

The hardware implementation for the reduced current measurement control algorithm was evaluated by design and experimentation of three-phase four-wire SAPF. A 3-phase diode-bridge rectifier with the R-L load as the nonlinear load is connected to AC mains to demonstrate the effectiveness of the SAPF with the reduced current measurement control method. A 1-phase diode-bridge rectifier with the R-C load is connected to AC mains to make unbalanced load.

The aim of the SAPF system is to compensate for the current harmonics produced by a diode-bridge rectifier of 10 kVA. The dc links of active filters are connected to a common dc capacitor of 1100 microfarad and 700 V DC. The diode-bridge rectifier is considered a harmonic producing load identical to a dc power supply that can found in any power electronics based system.

The control technique is implemented on the TMS320F28335 DSP board. F28335 DSP has an internal 68 kB RAM, 2 kB OTP ROM, 512 kB flash, 18 channels pulse width modulation (PWM), 12-bit 16 channels analog-to-digital (A/D) converters, expansion interfaces and parallel port JTAG interface. It can perform parallel multiply and arithmetic logic unit (ALU) on integer or floating point data in a 6.67 ns single cycle instruction time with a peak computation rate of 150 million instruction per second (MIPS).

Fig. 8. Show the photograph of the SAPF experimental prototype system. The source voltage and current signals are measured LEM hall-effect sensor. Semikron SEMIX 101GD128Ds IGBT modules

and the CONCEPT 6SD106EI six-pack IGBT driver modules and Semikron SKHI61 IGBT driver are used for driving the IGBT switches in power part of the SAPF system. IGBT driver module has short circuit and over current protection functions for every IGBT and provides electrical isolation of all PWM signals applied to DSP. Fig. 9 shows (a) experimental results for source current (i_{Sabc}) before and after filter operation (b) and current (i_{Sabc}) after filter operation. Source current becomes sinusoidal and in phase with the source voltage; hence, both harmonics and reactive power are compensated simultaneously. Fig. 10 shows experimental results for source current (i_{Sa}) harmonic spectrum before and after filter operation. Before harmonic compensation the THD of the supply current was 29.13% and after the harmonic compensation, it was reduced to 5.75% which complies with the IEEE 519 harmonic standards.

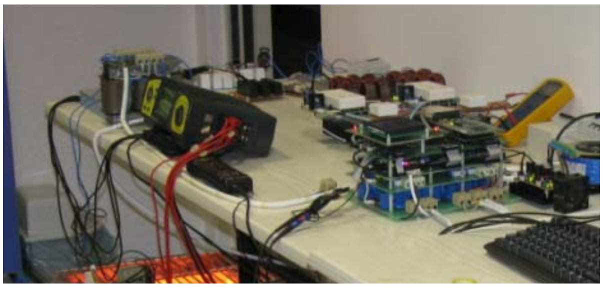

Fig. 8. The photograph of the SAPF laboratory system.

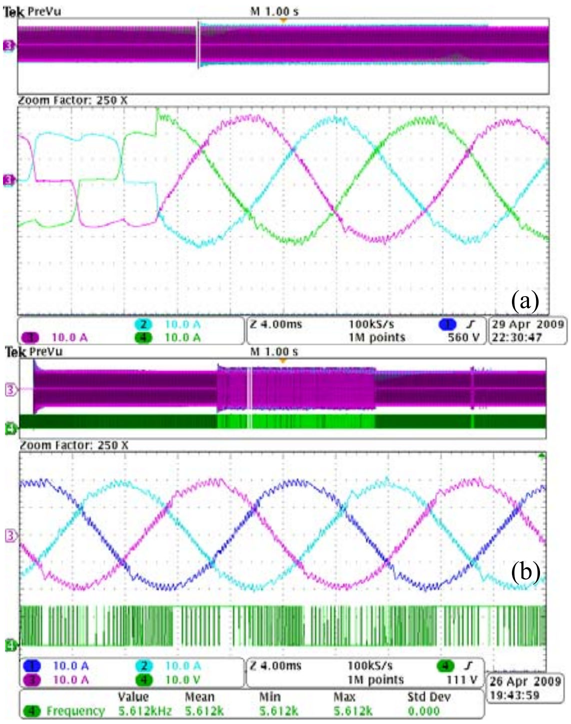

Fig. 9. (a) Experimental results for source current(i_{Sabc}) before and after filter operation (b) and current(i_{Sabc}) after filter operation.

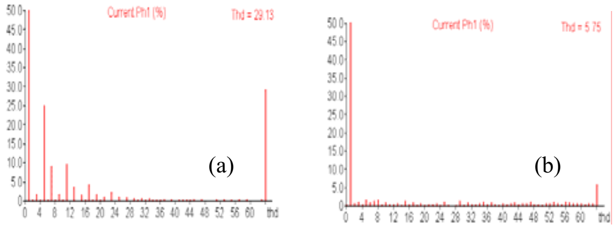

Fig. 10. Experimental results for source current(i_{Sa}) harmonic spectrum (a) before and (b) after filter operation.

Fig. 11. show experimental results for DC link voltage and source current(i_{Sa}) before and after load variation (load step up), SAPF tested under dynamical and steady-state load conditions under load changing. Fig.12. show experimental results for source currents (i_{Sabc}) and neutral current i_{Sn} Fig.13.show results for load neutral (i_{Ln}), filter neutral (i_{Cn}) and source neutral current i_{Sn} before and after filter operation.

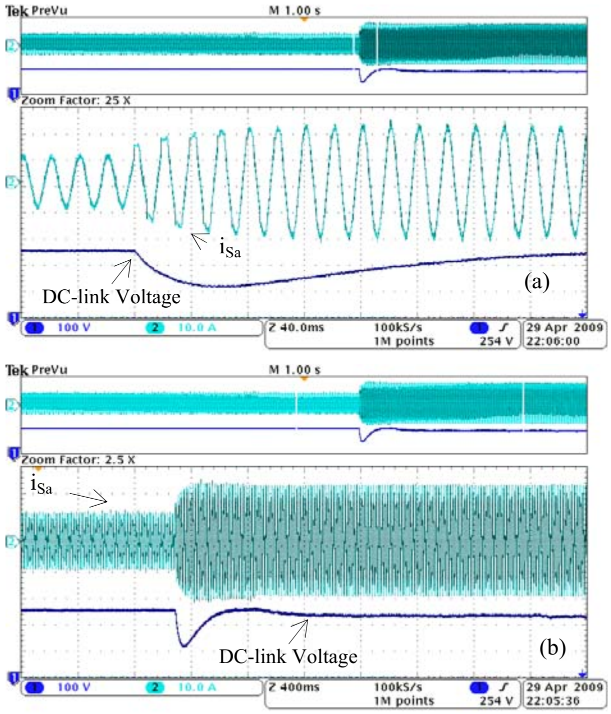

Fig.11. (a) and (b) Experimental results for DC link voltage and source current(i_{Sa}) before and after load variation (load step up).

These experimental results given above shows that the harmonics compensation features of SAPF, by appropriate control of shunt APF can be done effectively. SAPF with reduced current measurement based control method can be compensating neutral, harmonic and reactive currents effectively, in the unbalanced and distorted load conditions.

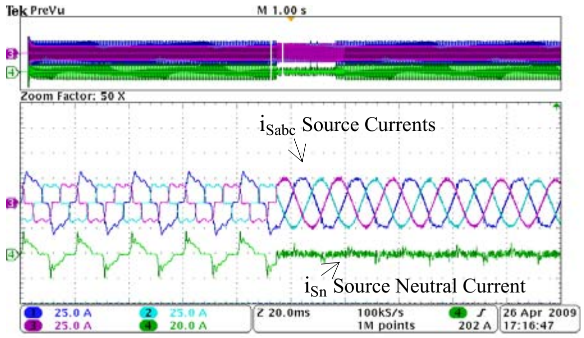

Fig.12. Experimental results for source current (i_{Sabc}) and neutral current i_{Sn} before and after filter operation

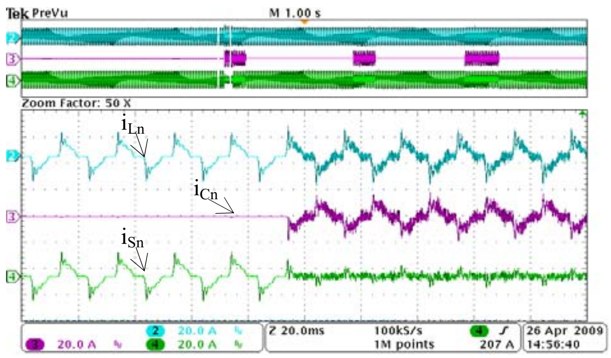

Fig.13. Experimental results for load neutral (i_{Ln}), filter neutral (i_{Cn}) and source neutral current i_{Sn}

5. Conclusion

In this paper, proposed control method based on reduced current measurement for shunt active power filter with only source current detection is investigated. Detection of neither load line current nor APF output current is not required. Therefore, computations and circuit implementation of the control system become quite simple compared to the conventional load current detection algorithms. In order to confirm the effectiveness of this control algorithm, the approach has been tested through the simulation and experimental validation.

Experimental test results using a TMS320F28335 DSP are given to demonstrate the performance of the reduced current measurement based control method for the shunt APF. Both simulations and experimental results confirm that the reduced current measurement based control method for the shunt APF has some advantages simple and easy to implement.

The results obtained have clearly shown that, even using only source current measurement, the APF performance is quite similar to that of standard solutions. Moreover, as the circuit needs only supply current feedback signals where the load CSs can be saved, the circuit design can be thus simplified significantly. Experimental results obtained from a laboratory model of 10 kVA, along with a theoretical analysis, are shown to verify the viability and effectiveness of the control method under non-linear and unbalanced load conditions.

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