Design of a simple OTA-Based Mixed-Signal Controller for Adaptive Control System of Shunt Active Power Filter

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Abstract: - This paper presents a simple mixed-signal controller using OTA (Operational Transconductance Amplifier) – based circuit for the adaptive control system of shunt active power filter (APF). The DC bus voltage detection method is proposed for the control scheme. The simple OTA multiplier circuit, OTA-C Canonical second-order filter circuit and OTA-C plus OTA summator circuit is designed for the reference-sine-wave signal generator including Low Pass Filter and PI controller. The LM13700 is represented for the OTA simulated model which is developed for using with the 50 Hz three-phase three-wire system utility. The advantage of using OTA-based circuits is its adaptive control and real-time processing which is suitable for high frequency power switches of the active power filter without using A/D converter. The simulation results show that OTA-based circuit can be used as the adaptive controller of APF which is simpler design compared to DSP, moreover, it can be fabricated in one single chip by using CMOS technology.

Key-Words: active power filter, adaptive, circuits, controller, mixed-signal, OTA, simple

1 Introduction

The use of nonlinear load power electronic component connected to power systems cause harmonic currents and harmonic voltages. Harmonics are the major source of waveform distortion, the harmonic control in electric power system has been described in several standards such as IEC 61000, G5/4 and IEEE 519 [1]. Active Power Filters (APFs) are the new trend in harmonic filtering technology that can be used to eliminate harmonic currents and voltages. APFs are operated dynamically which are more flexible than the use of passive filters that normally carried out static operating conditions.

The types and control methods of APFs have been reviewed as shown in [2]. A number of recent papers [3]-[12] are introduced for references. APFs normally installed on the power distribution systems [3],[5] and most common control strategy for APF that widely used is based on "d-q theory" which using digital controller [3],[4],[8],[9],[11]. However, since the front-end of the digital controller requires A/D converter which cause conversion time delay so that the switching frequency is limited. The Neural filtering method [12] and new control of APF are proposed as[6],[7]. The hardware FPGA controller [10] is proposed instead of DSP to give simpler implementation, however, the A/D converter is still required which gives the delay time computation.

OTA (Operational Transconductance Amplifier) [13], [14] is the adaptive device that implemented for adaptive circuit and used for adaptive control and real-time processing control of APF as introduced in [15] .

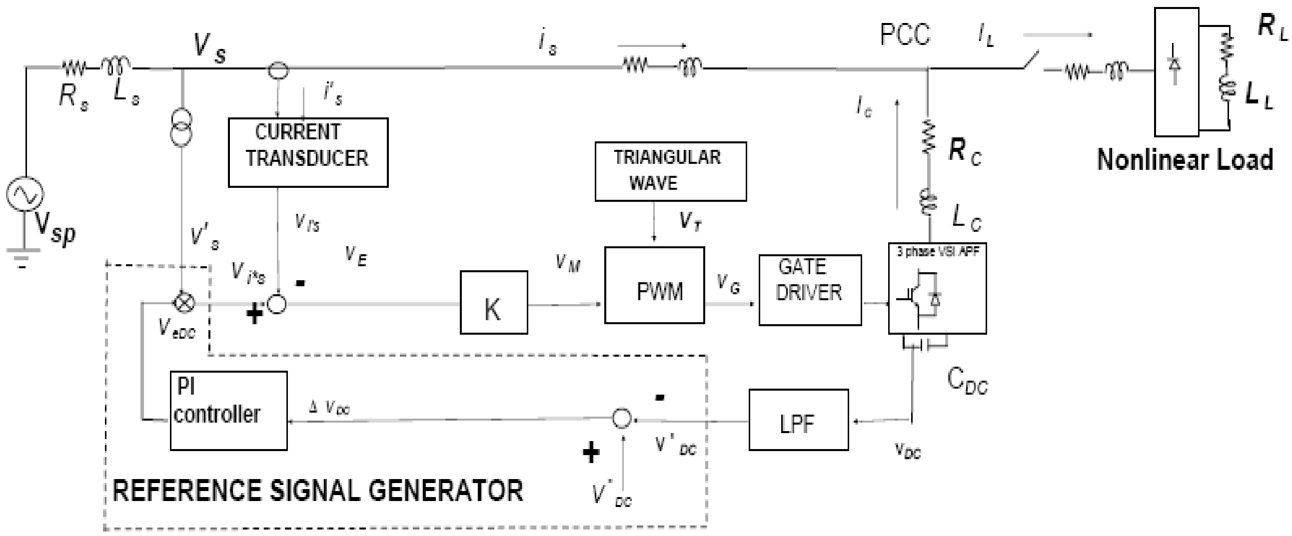

Fig. 1 Control Block diagram of the proposed APF

OTA&CCII-based circuit has been introduced in [16] and [17], the simulation results show that the parameter can be applied to the design of controller of the control blocks.

Unlike other analog devices, the improved OTA is used as analog processing which can reduce the signal drift problem. It has simpler structure and electronically tunable characteristic so that its designed circuits have the lower cost, simpler and smaller size circuitry compared to DSP. It has wide bandwidth which can work with the high frequency power switches in order to eliminate the higher order of harmonics. Moreover, it can be fabricated in one single chip by using CMOS technology.

This paper presents the novel development of the control blocks design using OTA-based circuit for the controller of APF. There-phase shunt Active Power Filter using Pulse Width Modulation Voltage Source Inverter (PWM VSI-APF) is selected for APF power circuit since it has more practical and ease of control compared to the other type of APFs. The DC bus voltage detection method [2], [3], [17] is used for “outer-loop-feedback control” between harmonic voltage and compensation current. The benefit of using DC bus voltage detection method compared to load current detection method [15] is to eliminate the current transducers at load side. The performance of the APF and its controller are investigated.

The APF control scheme is proposed in section 2 to summarize each block diagrams and determine the equations. The detailed analysis of OTA-based circuit is discussed in section 3. The computer simulation results are provided in section 4 and Section 5 gives a conclusion.

2 Proposed Control Scheme

Fig .1 shows the improved control block diagram of the three-phase shunt VSI APF connected to the three phase AC distribution system voltage ,v_S , (Phase to neutral) , supplying the nonlinear load current, i_L . The expected performance of APF is to maintain the main current , i_S , as a sine wave and in-phase with the main voltage , v_S .APF is controlled by the control block diagram circuit in order to generate the required compensation current , i_C . The DC capacitor, C_{DC} , is used as energy storage element and average voltage of the DC capacitor is maintained at a constant value but the voltage fluctuation cannot be avoided by the transient of load changing and by the reactive power flow. The control blocks are introduced, concepts as followings:

1) The reference-sine-wave generator signal block introduced the reference signal voltage , $\mathbf{v_{IS}}^*$. It can be defined by the multiplication of changed in feed back DC bus voltage (V^*_{DC} – $\mathbf{v_{DC}}$) and v_S since the amplitude of such signal depends on load current and in-phase with the source voltage. The Low Pass Filter

and PI controller is required for filter out the ripple of detected DC bus voltage fluctuation and for regulating the DC bus voltage respectively.

$$v_{IS}^{*} = v_{eDC} * v_S \qquad (1), \text{ where}$$

$$v_{eDC} = K_P \Delta v_{DC} + K_I \int \Delta v_{DC}\, dt \qquad (2)$$

$$\Delta v_{DC} = (V^{*}_{DC} - v'_{DC}) \qquad (3)$$

; v'_{DC} = output signal from Low Pass Filter of the detected DC bus voltage

2) The summator block gives the error signal, v_E, for feedback control which is the summation of v_{IS}^{*} and $-v_{IS}$ signal

$$v_E = v_{IS}^{*} - v_{IS} \qquad (4)$$

3) Modulation signal, v_M, is the output signal from error signal amplifier

$$v_M = K\, v_E \qquad (5)$$

4) PWM block gives gating signal, v_G, from the comparator of fixed-frequency triangular wave, v_T, and modulation signal, v_M.

3 Circuit Descriptions

The Reference-sine-wave Generator block as shown on Fig.1 is the main part for adaptive control of APF, It can be designed by using simple OTA-multiplier, OTA-PI Controller and OTA-Low Pass Filter as described in equation (1), (2), (3) respectively. The OTA summator block is used in PI controller block and also used for error signal detection as described in equation (4) & (5). The benefit of using OTA for voltage summator block is to reduce the resistive component and that for the further design of single chip fabrication. The PWM block shall be made of digital chip and to combine with OTA processing unit as mixed-signal controller.

3.1 OTA Multiplier

The multipler block as shown on fig.1 is made by only one simple OTA. The bias current of OTA can be selected as the function of v_{eDC} of the equation(1); the v_{eDC} is detected from the output signal from PI controller.

From OTA's transfer function & circuit in fig.2

$$i_O = g_m(v_{in}^{+} - v_{in}^{-})\ ;\ g_m = k\, i_B\,.$$

Where $i_B = (v_{eDC} - (-V_{CC}))/R_{B1}$

Therefore, $i_O = g_m v_S$

$$= k\,((V_{CC} + v_{eDC})/R_{B1})\, v_S \qquad (6)$$

Therefore, output of OTA- multiplier is in-phase with the supply voltage, v_S, and having the magnitude adaptively varies corresponding to the change of the load current measured by the v_{eDC}.

The OTA–LM 13700 is used for computer simulation to see non-ideal effect of the multiplier. The result shows that only one OTA can be used as the multiplier and has wide bandwidth up to MH_Z range as shown on fig.3

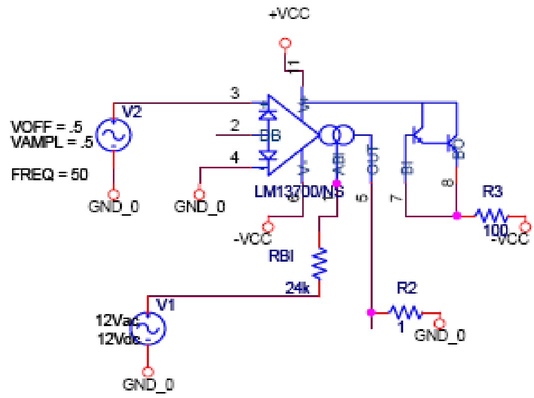

Fig.2 OTA-multiplier circuit

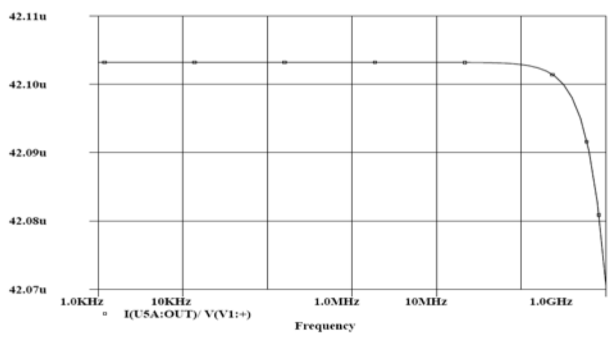

Fig.3 Frequency Response of the OTA Multiplier (i_O/ v_{eDC})

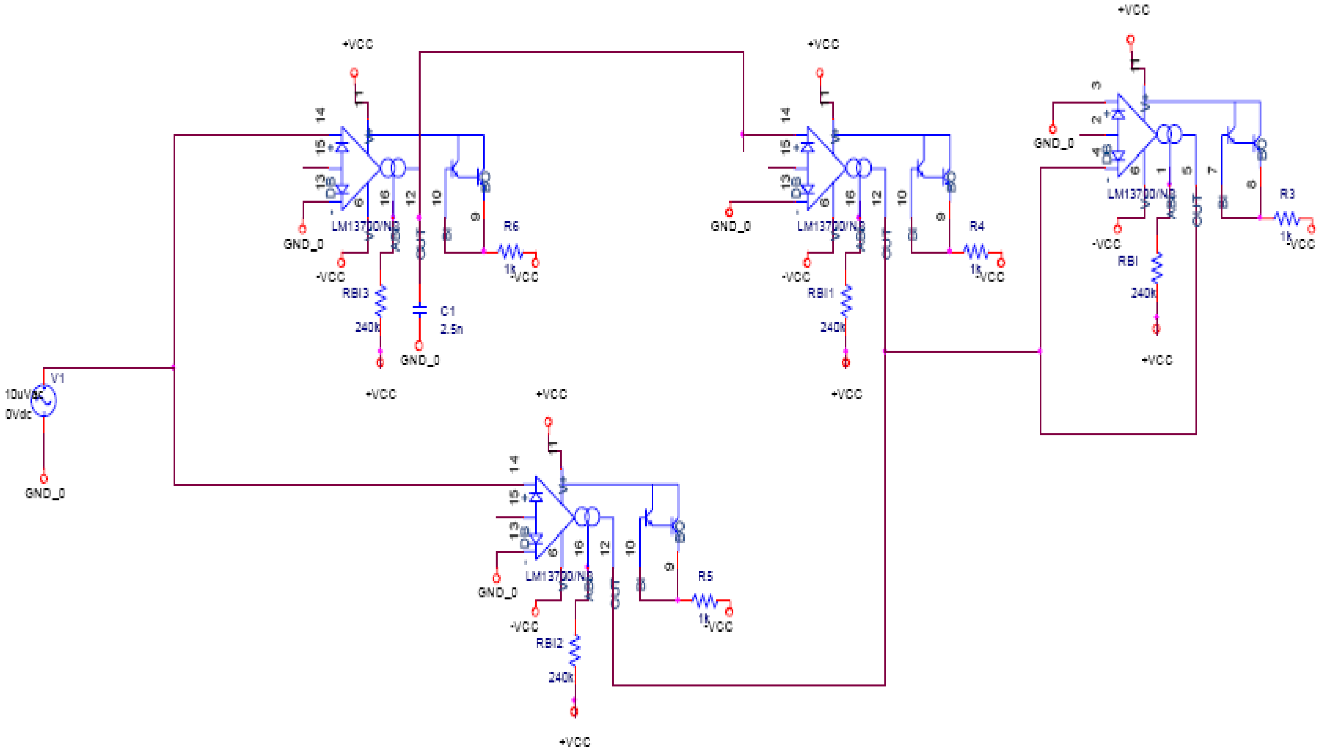

Fig. 4 OTA-PI Controller Circuit

3.2 OTA-PI Controller

The PI controller block according to equation (2) can be designed by using OTA-C [17] for integrator function and OTA voltage summator to combine both proportional and integral control . The OTA-PI controller circuit is shown as Fig.4.

From OTA integrator circuit;

$$v_{O\ OTA\text{-}C} = (1/C)\int i_O\, dt = (g_m/C)\int v_I\, dt \qquad (7)$$

The summation of signal from input and output of OTA-C integrator gives the OTA-PI-controller function

$$V_{PI} = v_I + (g_m/C)\int v_I dt \qquad (8)$$

Same as (2), where $K_P = 1$, $K_I = g_m/C$

Frequency characteristic of the PI-controller block using computer simulation is shown on fig.5 .

Result shows that the PI Controller keep the desired integral control gain constant, K_I , frequency up to MH_Z range.

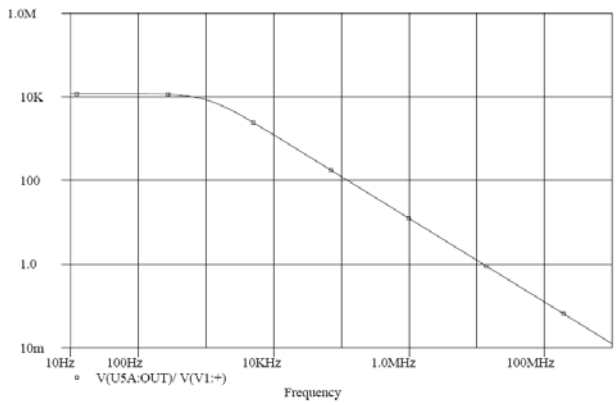

Fig.5 Frequency characteristic of the OTA-PI Controller

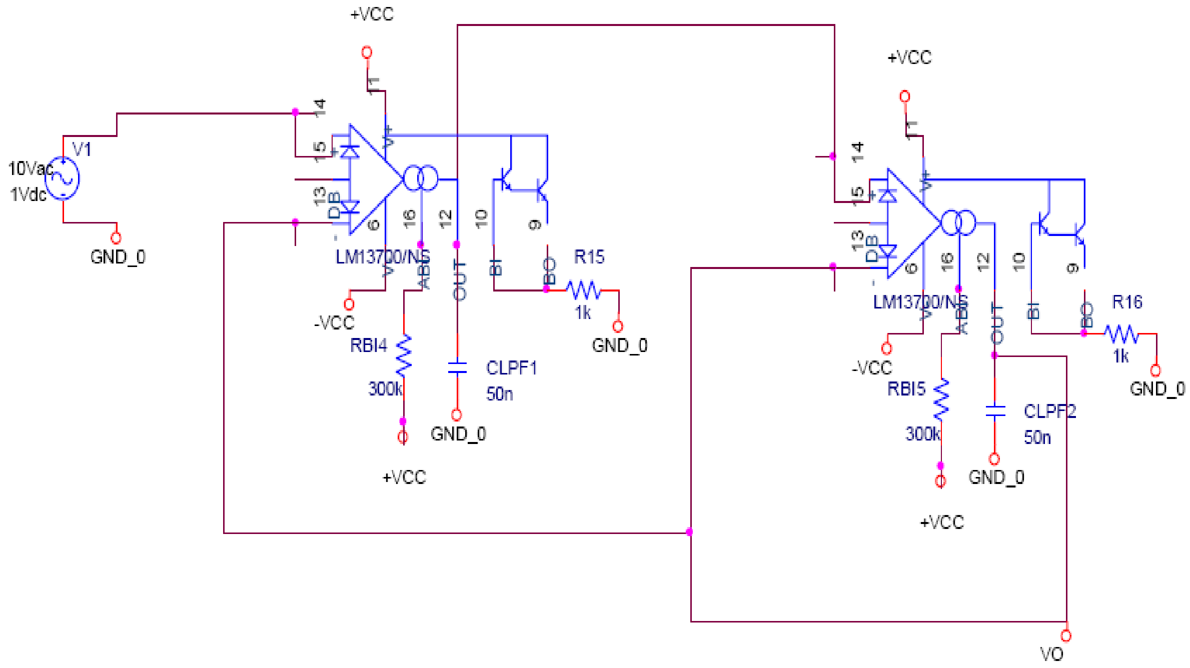

Fig.6 OTA-Low Pass Filter Circuit

3.3 OTA-Low Pass Filter

The Low Pass Filter (LPF) block as shown on Fig.1 according to equation (3) can be designed by Distributed-Feedback(DF) OTA-C Structure and using simplest or canonical second-order filter [13] which use two-OTA-C , g_{m1} & g_{m2} , for the Low Pass Filter output function as shown on Fig.6 .

By Laplace Transformation, The second-order LPF's transfer function is as followings:

$$\mathbf{V_O(s)} = \mathbf{V_i(s)} /(\tau_1 \tau_2 \mathbf{s}^2 + \tau_1 \mathbf{s} + 1) \qquad (9)$$

Where $\tau_1 = C_1/ g_{m1}$, $\tau_2 = C_2/ g_{m2}$

The pole angular frequency, $\omega_0 = \sqrt{1/ (\tau_1 * \tau_2)}$,and pole quality factor, $Q = \sqrt{(\tau_1 / \tau_2)}$, of the LPF can be orthogonally tunable by independently adjusting τ_1 and τ_2 of the circuit.

The proposed OTA-LPF for APF is to eliminate the ripple of the dc bus voltage cause by switching of the APF. The frequency characteristic of LPF output , at ω_0 = 40,000 , for Q=1 & 10 is shown as fig.7 & 8 respectively.

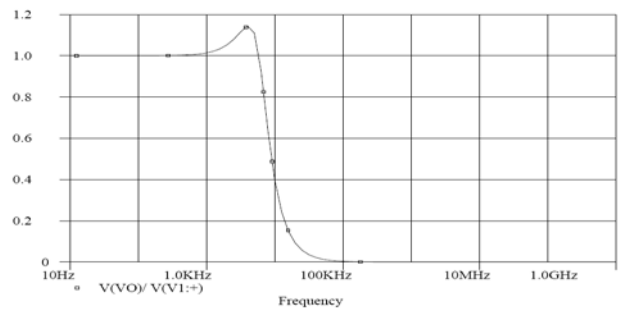

Fig.7 Frequency characteristic of the OTA-PI LPF for Q = 1, ω_0 = 40,000

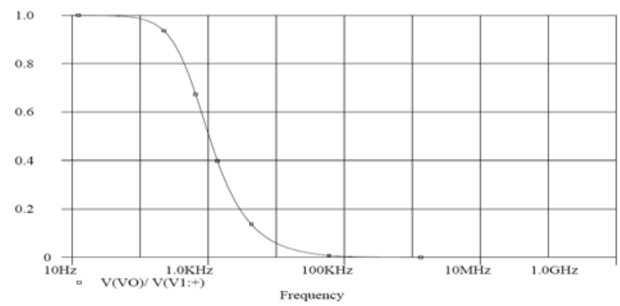

Fig.8 Frequency characteristic of the OTA-PI LPF for Q = 10, ω_0 = 40,000

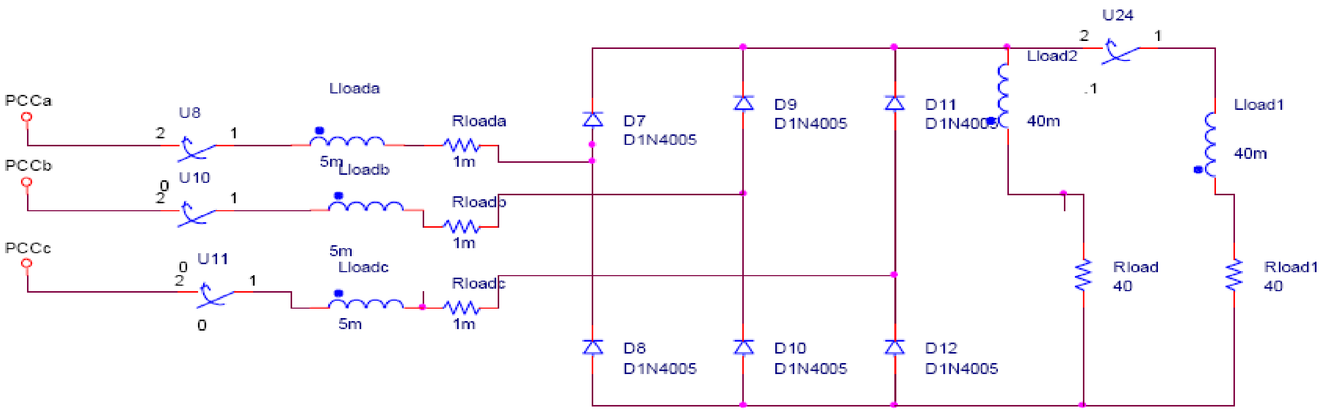

Fig.9 Three-phase diode bridge rectifier using as non-linear load circuit

3.4 Circuit Parameter

The proposed APF systems is made of three-phase IGBT based VSI bridge with link inductor (L_C, R_C) and a DC bus capacitor, C_{DC}. A three-phase diode bridge rectifier with two-step resistive-inductive load (L_l , R_l), according to circuit shown on fig.9 is fed by a three-phase, three-wire, 50 Hz, AC main with line impedance (L_S , R_S).

The Pulse Width Modulation (PWM) circuit is made of triangular wave generator and voltage comparator as shown on fig.10.

Table 1 summarizes power source, APF system and nonlinear load and Table 2 summarizes specification of the control circuit using for computer simulation in this paper.

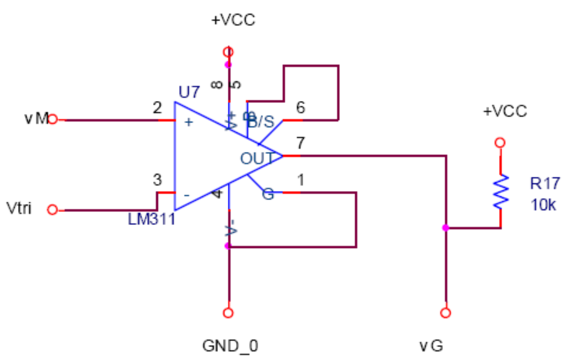

Fig.10 Voltage comparator using as PWM circuit

Table 1. Parameter of the Power Circuit

Power Source 3Φ 3 W, 50 Hz	
Supply phase voltage, v_S	28Vrms
Source Resistance, R_S	1mΩ
Source Inductance, L_S	1mH
Nonlinear Load-Bridge Rectifier3Φ 3 W	
Resistance, R_L	40Ω
Inductance, L_L	40mH
APF System-3Φ IGBT based VSI Bridge	
Switching frequency, f_S	20kHz
DC bus voltage, V_{DC}	100 V
DC capacitance, C_{DC}	1100µF
Resistance, R_C	555mΩ
Inductance, L_C	2.7mH

Table 2. Parameter of the control Circuit

OTA – LM 13700	
Input signal, v_{IN}	+/- 1 V
Output current, i_O	1µA -1mA
Bias current, i_B	1µA - 1mA
Transconductance, g_m	10µS-10mS
Gate driver Circuit	
Triangular wave	+/- 1 V
PWM-comparator	LM 311

4 Simulations Results

By computer simulation, ORCAD-Spice as the circuit-oriented simulators, the OTA-LM13700 is used as the major control device as mentioned in section 3. The performance of the proposed APF is discussed by the results of tested load in steady-state and under step change of three-phase non-linear load current.

Fig.11-14 shows the simulation results of the proposed APF tested with a three-phase non-linear load, i_L ,peak current = 1.5 A., Resistance, $R_L = 40\Omega$, Inductance, L_L = 40mH, the current signal is shown as fig.11. The switching frequency of 20 kHz is used. The time-domain (transient) analysis is investigated and found that, at steady-state, the proposed shunt APF inject the compensation current, i_C , shown as fig.12 given the results of source current containing fundamental current in-phase with the source voltage, shown on fig. 13 . The DC bus voltage is shown as fig. 14.

The performance is investigated at harmonic current up to 31^{st} order (1550 Hz) and found that the THDi of main source current is decreased from 23 % to 4 % which is less than 5% as required by IEEE 519 standard.

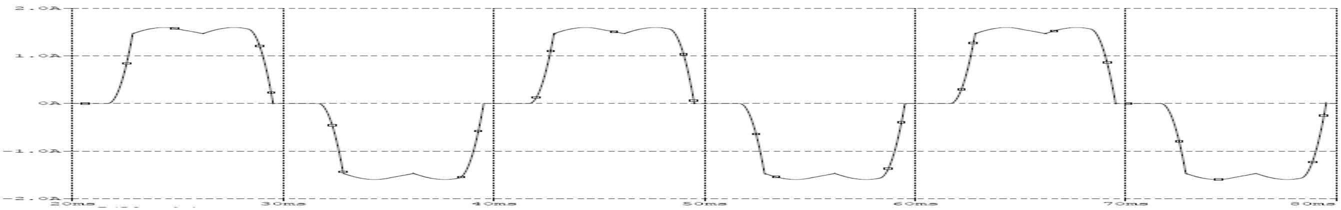

Fig.11 Non-linear Load current (steady-state)

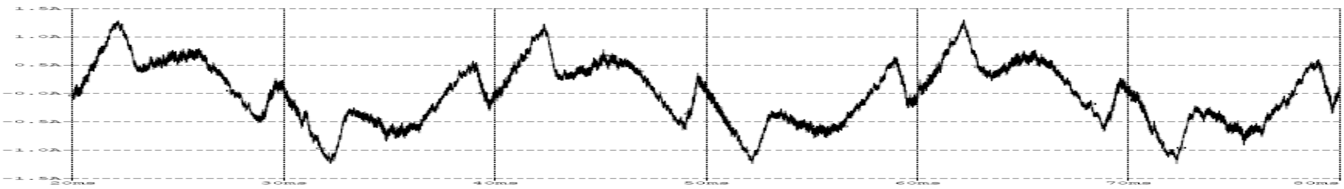

Fig.12 Compensation current fed by APF (steady-state)

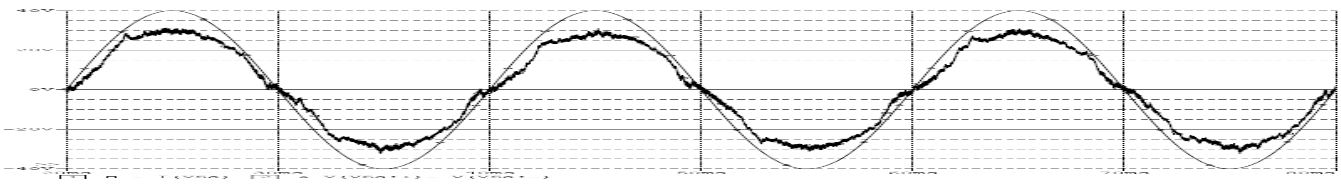

Fig.13 Source Current & Source Voltage (steady-state)

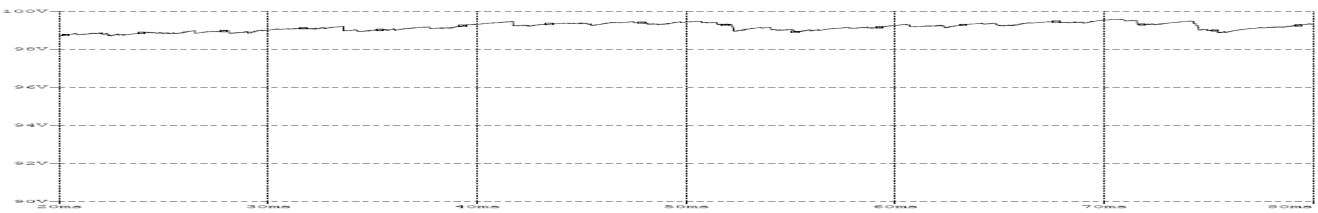

Fig.14 DC bus voltage (steady-state)

Fig.11-14 Simulation Results of the proposed APF with a three-phase non-linear load

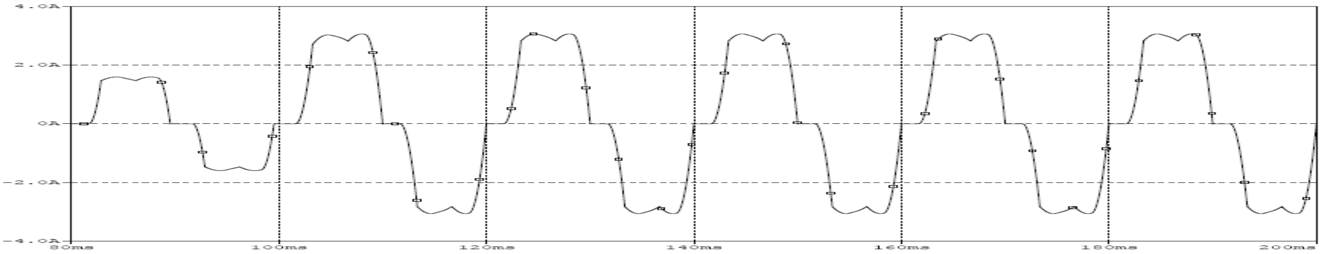

Fig.15 Non-linear Load current (transition period)

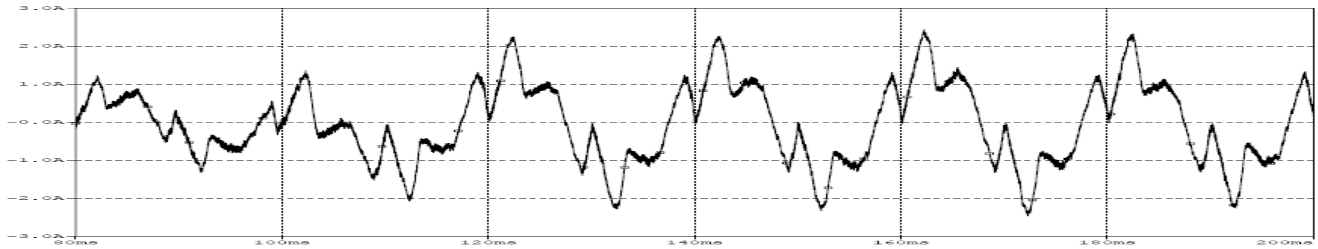

Fig.16 Compensation current fed by APF (transition period)

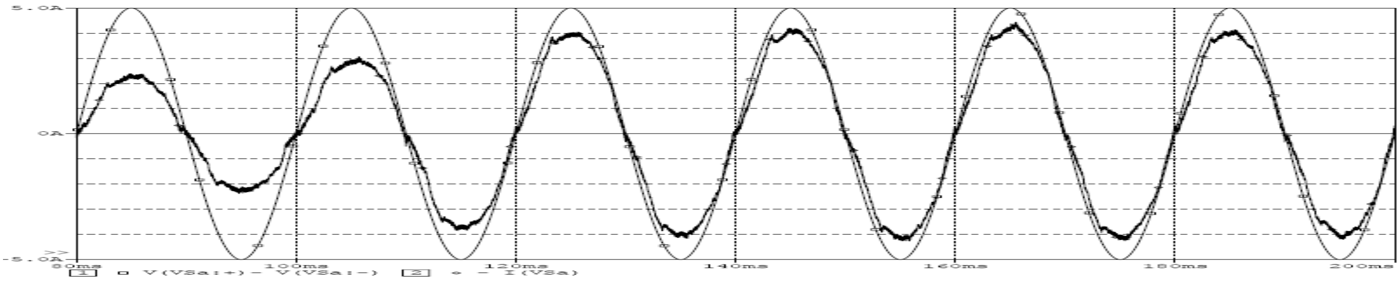

Fig.17 Source Current & Source Voltage (transition period)

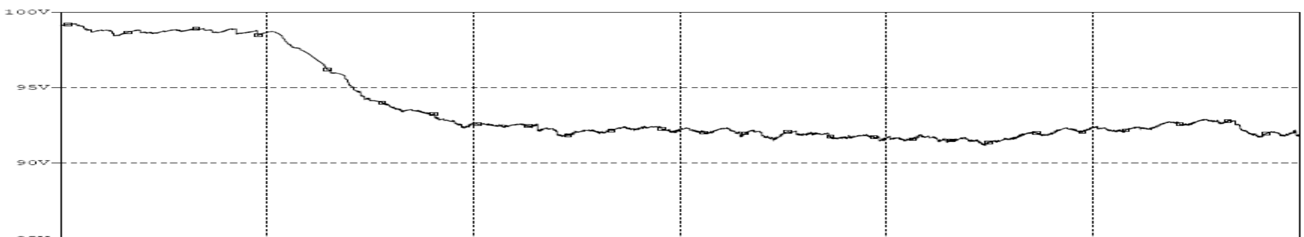

Fig.18 DC bus voltage (transition period)

Fig.15-18 Simulation Results of the proposed APF under step change of three-phase non-linear load

Fig.15-18 shows the simulation results of the proposed APF tested under step change of a three-phase non-linear load from 1.5 A to 3 A, the transition period of load current signal is shown as fig.15. The time-domain (transient) analysis is investigated and found that the proposed shunt APF can be adaptively control by the settling time approximately 60 ms or 3 cycles.

5 Conclusion

In this paper, The DC bus voltage detection method is proposed for the control scheme of shunt APF. The LM13700 is represented for the OTA simulated model which is developed for using with the 50 Hz three-phase three-wire system utility. The advantage of using OTA-based circuits is its adaptive control and real-time processing which is suitable for high frequency power switches of the active power filter without using A/D converter. The Reference-sine-wave Generator block is the main part for adaptive control and designed by using OTA-C structure for the simple OTA-multiplier, OTA-PI Controller and OTA-Low Pass Filter. The OTA summator block is used in PI controller block and also used for error signal detection. The benefit of using OTA-C for the PI controller and LPF block and using OTA for voltage summator block is to reduce the resistive component and that for the further design of single chip fabrication. The PWM block shall be made of digital chip and to combine with OTA processing unit as mixed-signal controller.

The simulation results show that OTA-based circuit can be used as the adaptive controller of APF which is simpler design compared to DSP, moreover, it can be fabricated in one single chip by using CMOS technology. The simulation results show that the proposed OTA-based circuit can be effectively used with the PWM as the mixed-signal controller of the APF.

Future development is to improve the OTA-based controller for other type of APF and to combine PWM block to the OTA-based circuit for the design of mixed-signal chip.

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