PERFORMANCE EVALUATION OF SHUNT ACTIVE POWER FILTERS FOR DIFFERENT CONTROL STRATEGIES

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ABSTRACT

Performance and stability of shunt active power filters improves very much with the preferred current control strategy. Supply currents are made sinusoidal with proposed control technique consisting of two sensors at the supply side and absence of harmonic detector which is present in the conventional control scheme of shunt APF. Performance of Shunt Active Power Filter was compared with three control techniques namely PI controller; PI -Vector PI controller; Fuzzy-Vector PI controller with both Six Switch Three Phase Inverter and Four Switch Three Phase Inverter. It was observed and proposed that SSTPI can be replaced with FSTPI, as it is having the comparable results of SSTPI with reduced hardware & thereby cost. The proposed technique is capable of mitigating harmonic currents and reactive power to achieve unity power factor condition at the supply side. Variations in the supply side currents in terms of harmonic distortion were presented in the paper for all the controllers at different loads and load changes.

Keywords: shunt active power filters, PI controller, fuzzy-vector PI controller, four switch three phase inverter.

1. INTRODUCTION

The use of semiconductor devices is essential to have control on a.c power to feed them to loads such as adjustable speed drives, SMPS, furnaces etc. As non-liner loads, these converters draw harmonic and reactive power components from supply mains which results so many power quality issues with poor power factor and decrease in system efficiency [1].

LC passive filters were normally used to debase the harmonic currents and capacitors to improve the load power factor due to their simple and low cost solutions. However passive filters are often large and heavy with fixed compensation and resonance problems. To handle the increasing harmonic pollution in the systems, a dynamic and adjustable solution was chosen by power engineers known as active filter.

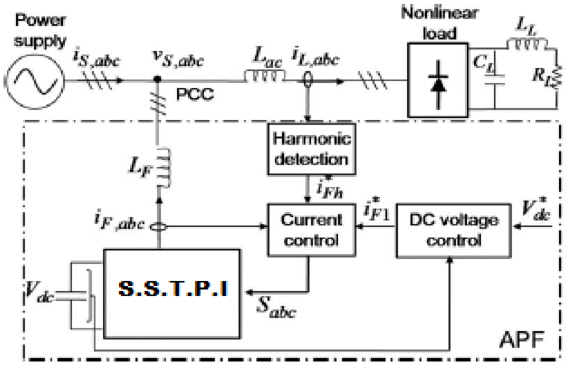

Figure-1. Traditional control scheme of APF.

Figure-1 shows a traditional control scheme of APF which consists of blocks like load current measurement, detection of harmonic current, reference pulse generation and filter current control to generate harmonic currents having the same magnitude and opposite phase with the harmonics produced by the non-linear loads [2]. This results a supply current with fundamental component only. Various control techniques were developed like PID family of controllers, dead-beat control, resonant controller, hysteresis control which needs mathematical models and therefore sensitive to parameter variation. Sliding mode control does not need accurate mathematical model but requires the knowledge of parameter variation range. As Fuzzy Logic Controllers work with imprecise inputs, robust, handle nonlinearities and does not require accurate mathematical model, in the present scenario FLC seems to be viable controller for power electronic applications. For the present work, FLC along with VPI controller is used in APF and the results were compared with proportional- internal controller and PI- Vector PI controller under load and supply disturbances. For different loads, FSTPI and SSTPI configurations and supply disturbances, simulation results were observed with all the three controllers.

2. PROPOSED CONTROL STRATEGY

Harmonic current detection and tracking, load current and filter current sensors of a typical control scheme are eliminated in the proposed control scheme which reduces the complexity in the design process. As front-ends of a.c. drives, 3- ϕ diode rectifier is normally used. A 3- ϕ voltage source inverter connected in parallel with nonlinear load at point of common coupling through an inductor forms an APF. At dc–link side of the inverter a large capacitor is placed for energy storage of APF. The detailed block diagram of proposed control strategy is shown in Figure-2.

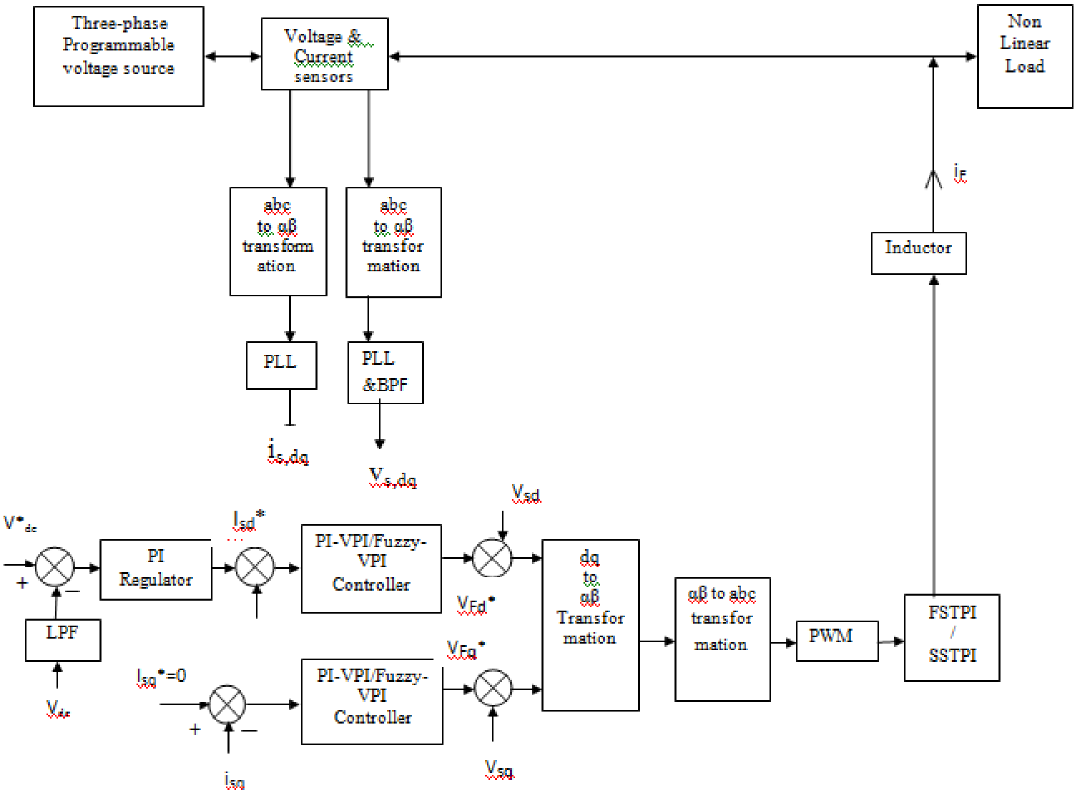

Figure-2. Proposed control strategy.

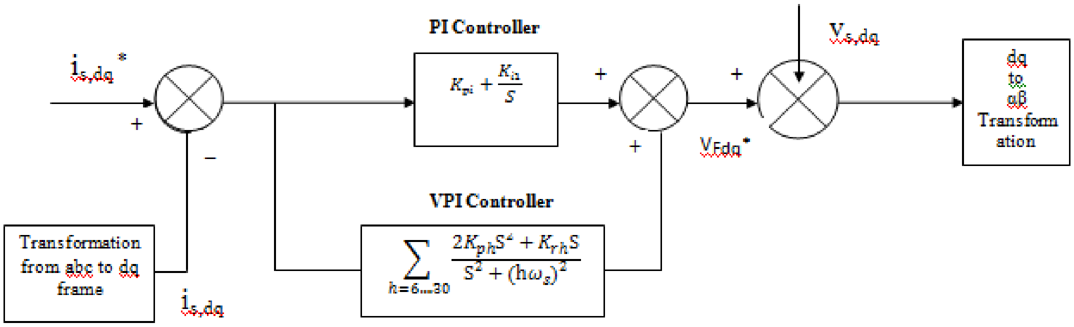

Figure-3. PI- VPI control scheme.

The block diagram of PI-VPI control scheme with gain representations is as shown in Figure-3.

The control gains K_{ph} and K_{rh} are kept constant and their values mentioned in Table-1[2].

Table-1. Gains of current controllers.

K_{p1}=4	K_{i1}=100	K_{p6}=0.8	K_{r6}=20
K_{p12}=0.6	K_{r12}=15	K_{p18}=0.3	K_{r18}=7.5
K_{p24}=0.1	K_{r24}=2.5	K_{p30}=0.1	K_{r30}=2.5

The proposed control strategy consists of two control loops namely dc-link voltage control loop and supply current control loop. For synchronization and coordination with different transformations phase lock loop is also used. Our aim is to keep the dc link voltage of active power filter constant. To do so, a PI regulator is used whose output is the reference active current.

$$i_{sd}^* = \left(K_{pdc} + \frac{K_{idc}}{S}\right)(V_{dc}^* - V_{dc})$$

Where K_{pdc} and K_{idc} are the proportional and integrator gains of PI regulator

V_{dc}^* = Reference dc-link voltage
V_{dc} = Measured dc- link voltage

The reference signal i_{sd}^* can be smoothened by using LPF to eliminate the ripples in the dc-link voltage. This dc-link voltage controller help's to deal with variations of the load also as we are measuring dc link voltage variations. By detecting and controlling the dc-link voltage shunt APF can recognize and respond against load variations indirectly without any load current measurement. By considering i_{sq}^* as zero, total reactive power caused by loads can be fully compensated and UPF condition can be achieved. To have a low cost topology, instead of SSTPI, FSTPI composed of four power switching devices and two split capacitors is used without degrading it's performance and the result analysis was shown for different conditions. The control signals of four switch APF can be obtained by

$$V_{Fa}^* = \sqrt{\frac{3}{2}}V_{F\alpha}^* + \sqrt{\frac{1}{2}}V_{F\beta}^*$$

$$V_{Fb}^* = \sqrt{2}\,V_{F\beta}^*$$

V_{Fa}^* & V_{Fb}^* → Control signals for leg a and b of four switch active power filter.

Distortions at the supply side are normal at distributed network and those will be taken care by having PLL and BPF tuned at the fundamental frequency of supply voltage. The system parameters used in the simulations are given Table-2 [2].

Table-2. System parameters.

Supply voltage RMS line-line	127V
Supply frequency	60Hz
5th harmonic supply voltage	10% of the fundamental component
7th harmonic supply voltage	5% of the fundamental component
DC-link reference voltage for the six-switch APF V^*_{dc}	260 V
DC-link reference voltage for the four-switch APF V^*_{dc}	420 V
DC-link capacitor for four-switch APF C_1=C_2	1000 μF
DC-link capacitor for six-switch APF C= C_1+C_2	2000 μF
Filter resistance R_F	0.05 Ω
Filter inductance L_F	2 mH
Nonlinear RLC load	$R_{L(\min)}$=12.5 Ω, $R_{L(\max)}$=20 Ω, L_L=1 mH, C_L=2200, μF

3. INDIRECT CURRENT CONTROL SCHEMES

A. PI controller

In the proposed control algorithm, supply current is directly measured by a sensor and will be regulated as sinusoidal signal by the current controller which is known as Indirect current control scheme. With this indirect current control, by using only PI controller it is impossible to achieve sinusoidal supply current because the supply currents are indirectly controlled by regulating the filter currents which are the non-sinusoidal signals [3]. Like in traditional control scheme, if the load currents are measured directly and a series of resonant controllers are tuned at high frequencies, we can achieve good current performance [4, 5]. There is a limitation of control bandwidth of PI controller due to which it is unable to regulate harmonic currents satisfactorily and the distortion [THD] is not within the standards. In order to achieve sufficient regulation of harmonic currents we must have multiple resonant controllers tuned at high frequencies. The transfer function of which can be

$$G(PR) = \sum_{h=odd} K_{ph} + \frac{2K_{rh}s}{s^2 + (h\omega_s)^2}$$

K_{ph} and K $_{rh}$ → Proportional and resonant gains of controller.
h → harmonic order
ω_s → fundamental frequency

Proportional to the number of harmonic currents needs to be compensated, the complexity and computational burden increases.

Number of harmonic currents can be reduced to 6n from 6n+1 by combining PI and resonant controllers which has the transfer function as

$$G(PI-R)=K_{p1}+\frac{K_{i1}}{S}+\sum_{h=6,12,18} K_{ph}+\frac{2K_{rh}S}{S^2+(h\omega_s)^2}$$

K_{p1} = Proportional gain
K_{p1} = Integrator gain
h = 6n is the order of harmonics in the fundamental reference frame.

Even it is good in performance, it consists of delay time and that term needs to be added which includes extra sampling parameters and increases the complexity. It also suffers with undesired peaks in the response which can be overcome by VPI controllers.

For the present work, PI controller is used for RL load and RLC load and the results were shown in Figure-4. It was observed that the total harmonic distortion of load current is 26.29% and source current is 11.3% for RL load and 39.49% and 12.7% for RLC load conditions.

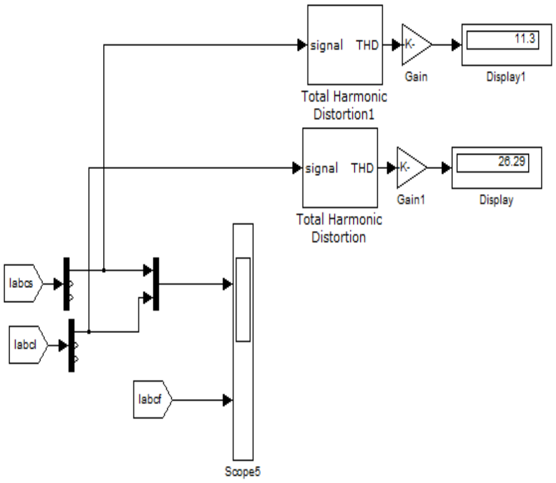

Figure-4(a). THD values for RL load.

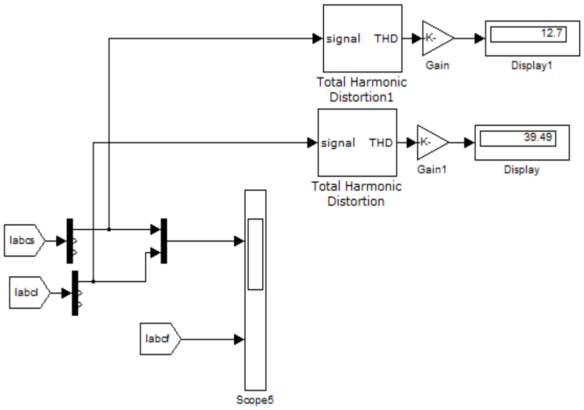

Figure-4(b). THD values for RLC load.

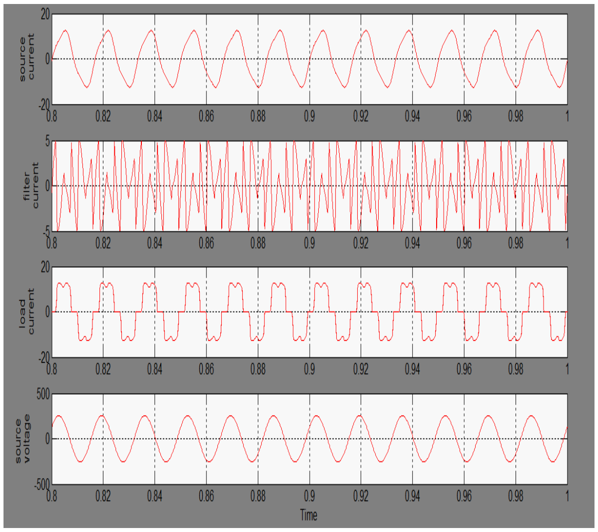

Figure-4(c). Waveforms for RL load.

Result shows that the harmonic currents are insufficiently compensated due to control bandwidth limitation of PI controllers. It was observed that the desired control target of the APF cannot be achieved by using only the PI controller.

B. PI -VPI controller

Due to pole-zero cancellation capability with inductor L_F, undesired peaks can be prevented by PI-VPI controller. Closed loop transfer function of PI-VPI controller can be defined as

$$G(T)=\frac{G(PI-VPI)G(LF)}{1+G(PI-VPI)G(LF)}$$

Where $G(LF)=\frac{1}{SL_F+R_F}$ and

$$G(PI-VPI)=K_{p1}+\frac{K_{i1}}{S}+\sum_{h=6,\dots,20}\frac{2K_{ph}S^2+K_{rh}S}{S^2+(h\omega_s)^2}$$

By tuning the gains property, VPI controller provides a unity gain and zero phase-shift. VPI controller is more selective and results better steady state performance if K_{ph} is a smaller value. However, too small K_{ph} will deteriorate the dynamic response of APF. For the present work Kph value is chosen according to Table-1.

At low frequency(less than 20 HZ), the gains of PI and PI- VPI controllers are high and comparable. But at high frequencies, the gain of PI controller is significantly reduced while PI-VPI controller produces very high gains for getting zero steady-state errors in compensating the harmonic currents.

In order to verify the superiority of the VPI control algorithm with PI control scheme, it was observed for same RL and RLC loads and the results were shown in Figure-5.

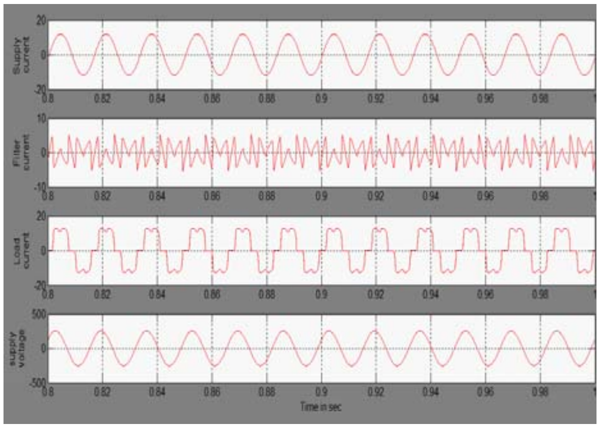

Figure-5(a). Waveforms for RL load.

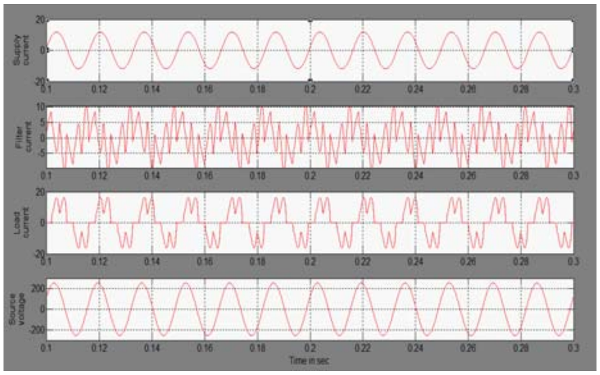

Figure-5(b). Waveforms for RLC load.

From the results it was observed that with PI-VPI control strategy, harmonic currents are effectively compensated and the supply current is made sinusoidal with a small total harmonic distortion factor of 1.63% where as the load current is having a total harmonic distortion of 26.29%. The transient responses with variation of loads of the system are also studied and the results were shown in Figure-6 and Figure-7.

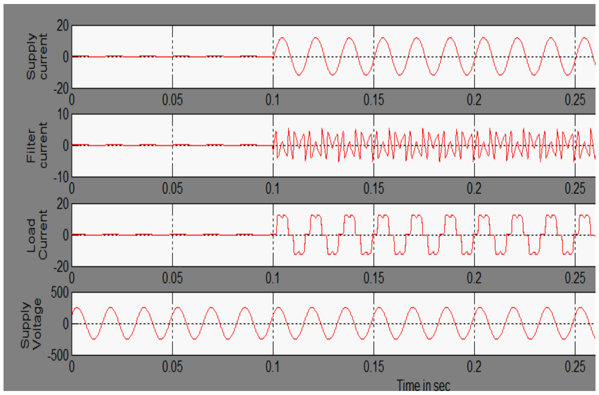

Figure-6. Transient response of control scheme under RL load when load is applied at 0.1sec.

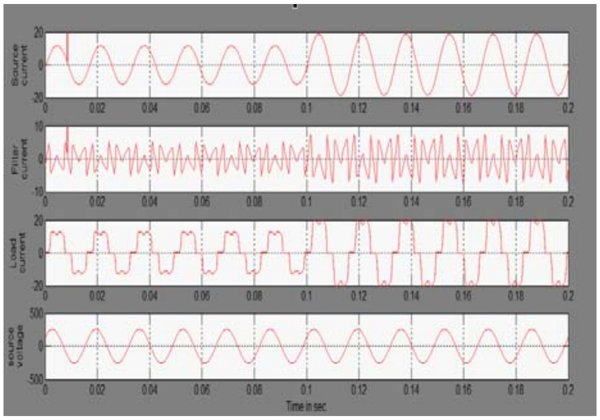

Figure-7. Transient response of control scheme under RL load with changed load.

It was observed from the results that, whenever the load is applied or changed, the filter current immediately responds to the change to compensate harmonic currents in the load and to make supply side current more sinusoidal and in phase with supply voltage. The same control strategy was applied for non linear RLC load also and the results were established. In order to check the effectiveness of PI-VPI control strategy in practical networks where distorted supply voltage condition normally exists, simulation was carried out under this condition. A Programmable voltage source is chosen so that 5th and 7th harmonic components were injected into the supply voltage with 10% and 5% magnitudes of the fundamental component. The harmonic compensation performance of the APF is not deteriorated by the distorted supply with only small increments in THD factors for both nonlinear RL and RLC loads and the results were shown in Figure-8.

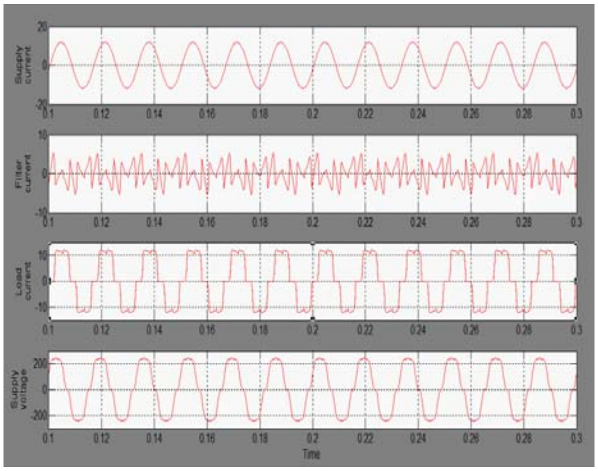

Figure-8(a). Waveforms for RL load with distorted supply.

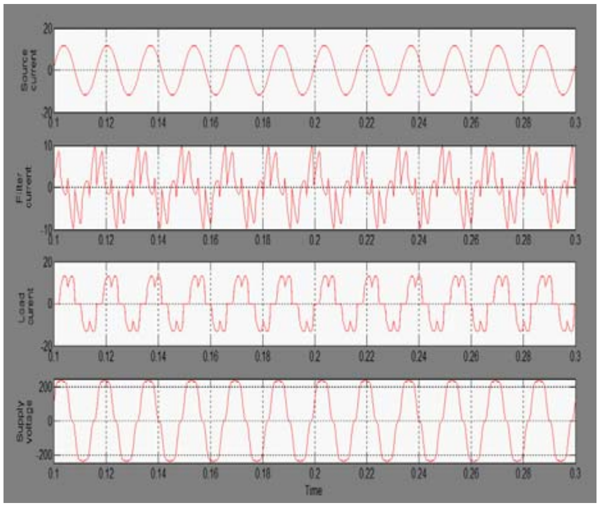

Figure-8(b). Waveforms for RLC load with distorted supply.

With Four Switch Three Phase inverter in the place of SSTPI all the conditions that is stead state performance, transient performance, distorted supply voltage conditions for nonlinear RL and RLC loads are verified and some of the results were shown in Figure-9.

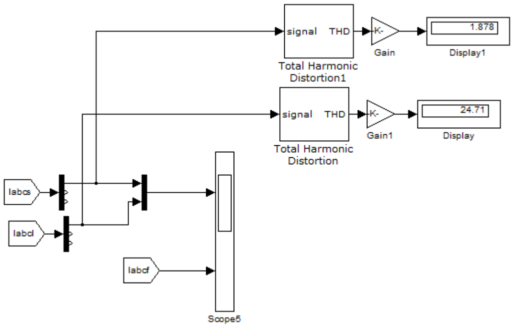

Figure-9(a). THD values for RL load with FSTPI.

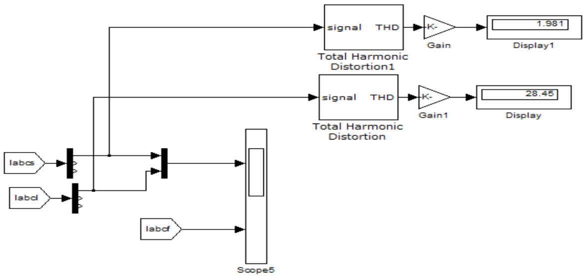

Figure-9(b). THD Values for RLC load with FSTPI.

C. Fuzzy-VPI controller

As Fuzzy controllers have more advantages than other controllers, in order to improve the performance of APF, in the place of PI Controller, Fuzzy controller is placed for the present work. Fuzzy logic controller has 3 functional blocks those are fuzzifier, evaluator and defuzzifier. It is a rule based system. All the rules are formed in "if then "format. Depending upon the measured input error and change in error the rules are executed with rule table [7]. Fuzzy controller block is used in the place of PI controller and all the conditions i.e. steady state, transient and distorted supply conditions were observed for both nonlinear RL and RLC loads and some of the results were shown in Figure-10.

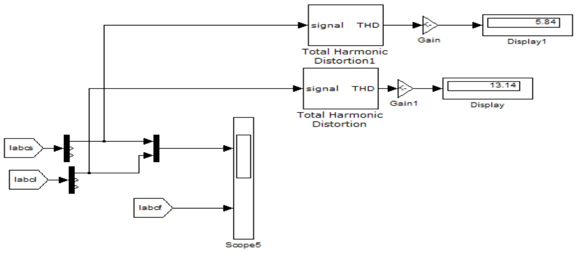

Figure-10(a). THD Values for RL load with Fuzzy.

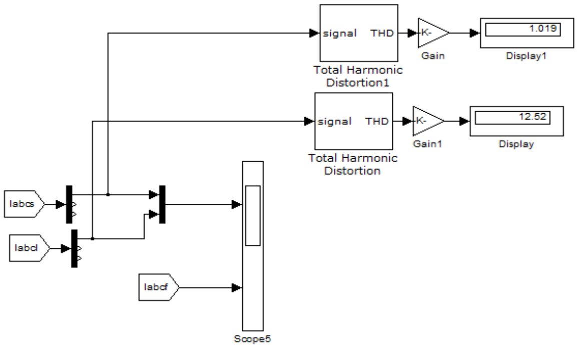

Figure-10(b). THD Values for RL load with Fuzzy-VPI controller (SSTPI - ideal supply).

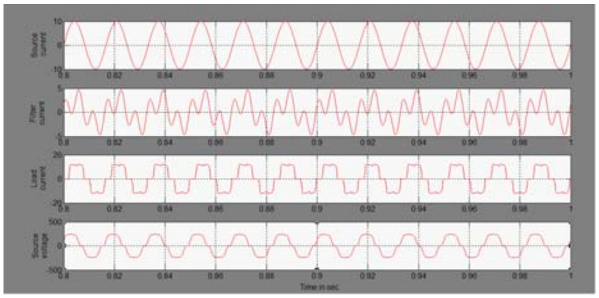

Figure-10(c). Waveforms for RLC load with Fuzzy-VPI controller (FSTPI - distorted supply).

4. CONCLUSIONS

Table-3. THD factors in percentage for different control strategies.

Load	Source current THD		Six switch APF with ideal supply		Six switch APF with distorted supply		Four switch APF with distorted supply	
	PI	FUZZY	PI-VPI	FUZZY-VPI	PI-VPI	FUZZY-VPI	PI-VPI	FUZZY-VPI
RL	11. 3	5. 13	1. 64	1. 01	1. 83	1. 05	1. 88	1. 16
RLC	12. 7	8. 1	1. 73	1. 03	1. 94	1. 02	1. 98	1. 27

Evaluation of shunt APF for difference current control strategies was performed. Indirect current control technique is used to make supply side current more sinusoidal and reduce the distortion. PI, PI-VPI, Fuzzy-VPI control strategies have been verified for steady state response, transient response and distorted supply conditions for nonlinear RL and RLC loads through various simulations. The supply current is almost sinusoidal and in phase with supply voltage for both PI-VPI; and FUZZY- VPI controller cases and it has distortions with usage of PI controller alone due to its control bandwidth limitations.

Absence of harmonic detector and load current sensors, replacement of SSTPI with FSTPI reduces the cost of the inverter, switching losses, and complexity of the control algorithm in practical cases. THD factors for all the control strategies with difference conditions are formulated as Table-3 and it was observed that all THD values are within IEEE Standards. Implementation of APF with FSTPI shows that the performance is not degraded and the distortion levels are nearer to SSTPI model. With Fuzzy-VPI controller we are having decreased THD values than PI-VPI controller and are proved as more advantageous than other control techniques. From the results it was observed that the load side distortions are also reduced with implementations of Fuzzy -VPI Controller.

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