2017 IEEE International Conference on Technological Advancements in Power and Energy (TAP Energy 2017)

Enhancement of Load Voltage Compensation using Positive Sinusoidal Sequence Regulator in Fuzzy Logic Controlled Three Phase Series Active Filter

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***Abstract*— This study proposes a controller for series active filter for enhancement in load voltage compensation. The controller consists of a positive sinusoidal sequence regulator based fundamental voltage calculator, a closed loop fuzzy logic based voltage controller and a pulse width modulation controller. Positive sequence sinusoidal signal regulator effectively eliminates the phase delay introduced while calculating fundamental voltage. Numerical simulations are done for different cases to verify the effectiveness of controller under different system conditions.**

***Keywords*—series active filter; positive sequence sinusoidal regulator; fuzzy logic; power quality; voltage sag; voltage swell; harmonics**

I. INTRODUCTION

Voltage sag, swell and harmonic distortions are the major power quality problems in distribution system utilities [1], [2]. Equipments in modern industrial plants, like process controllers, programmable logic controllers, adjustable speed drives etc. are very sensitive to these kinds of power quality issues. Voltage sags result in intermittent lock ups or garbled data in sensitive equipments like computers. Relays and contactors in motor starters may be affected by sags, which results in shut down of the whole process. Voltage swells may result in breakdown of supply equipments due to the over voltage condition. The effect of swell is accumulative and gradual. Distortions in supply voltage may result in mal-operation of the equipments. Harmonic components in voltage supply may result in reverse torque generation in induction motors and may result in overheating or failure of motors [3].

Conventionally passive filters are used for voltage compensation. Series active filters (SAF) are superior in compensation performance compared to passive filters [4]. With the emergence of IGBTs along with FPGAs and Hall-effect sensors, Series active filter is an appropriate and cost effective solution for compensating sag, swell and voltage harmonic components [5]. The control system of series active filter consists of a positive sequence fundamental voltage calculator. Conventionally positive fundamental voltages are calculated by using low pass filters [6]. Low pass filters introduce an additional phase lag and it affects performance of the series active filter. This can be overcome by cascading a lag compensator circuit, which increases the complexity and cost of the overall control system [6]. A stable closed loop voltage controller is needed for effective control of output ac voltage of the voltage source inverter. Since the accurate modelling of dynamic states of inverter is difficult, voltage controller design is a complex task [7], [8].

In this study, a series active filter load voltage compensation enhancement by using a positive sinusoidal sequence regulator (PSSR) is proposed and validated the performance of controller by numerical simulations. The design of voltage controller, for controlling the output ac voltage of inverter, is simplified by introducing fuzzy logic control. PWM controllers are used for generating switching pulses of the inverter. In first section, the control schematic of series active filter and the design of its components are illustrated. In second section the simulation results for different system conditions are shown which verifies the effectiveness of controller. Last section is the conclusion of the observations from the results.

II. CONTROL SCHEME OF SERIES ACTIVE FILTER

The overall framework of a series active filter connected at distribution level with non-linear loads at point of common coupling is shown in fig.1, which consists of a three phase voltage source inverter with IGBT switches, two dc link capacitors, a battery, a 3 phase LC filter at ac side, and isolation transformers to inject the compensating voltage in phase with the grid voltage. The basic principle of series active filter is that, it senses the changes in grid side voltage and injects compensation voltage in series with the grid voltage to nullify the change. The change can be a voltage sag, voltage swell or voltage distortion in grid voltage. The control scheme of the series active filter is shown in fig.2.

A peak detector detects the peak amplitude of the grid voltages V_{sa}, V_{sb}, V_{sc} in every cycle of their fundamental frequency. The grid voltage is divided with the corresponding peak amplitude values to get three phase unit amplitude signals, U_a, U_b, U_c which are in phase with the grid voltages. The unit amplitude signals are then transformed into αβ0 frame using (1) to get U_α, U_β, U_0.

$$\begin{bmatrix} U_\alpha \\ U_\beta \\ U_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{1}$$

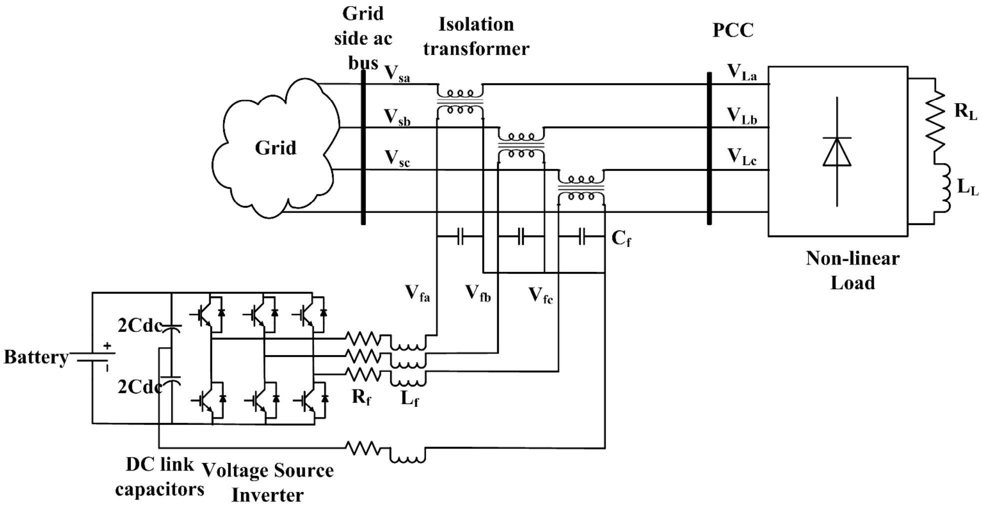

Fig. 1. Circuit diagram of series active filter

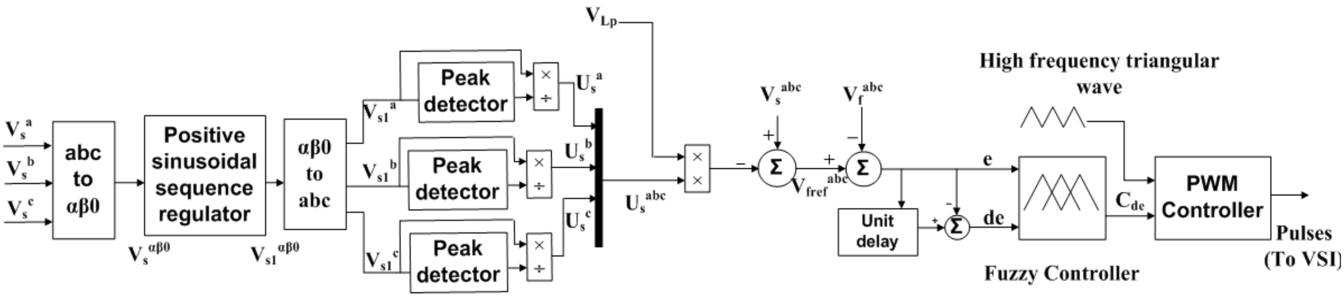

Fig. 2. Control schematic diagram of series active filter

A positive sinusoidal sequence regulator (PSSR) is used for detecting the positive sequence fundamental component. A sinusoidal signal integrator (SSR) is the main part of PSSR. The angular frequency of fundamental positive sequence components of the grid voltages is equal to the resonance frequency (ω) of SSR. So the positive sequence components are instantaneously integrated. When the input signal frequency is not equal to the resonance frequency of SSR, the integration output will be zero. A negative feedback loop to the SSR makes it a regulator, which can identify the fundamental component of positive sequence signal from the input signal [9]. The schematic diagram of PSSR is shown in fig.3. U_{α_1}, U_{β_1}, U_{0_1} are the fundamental positive sequence components of grid voltage in αβ0 frame. The constant K is sensitivity constant, which controls the response time and bandwidth of PSSR. The transfer function of PSSR can be written as shown in (2).

$$H(s) = K\frac{s+K+j\omega}{(s+K)^2+\omega^2} \quad (2)$$

Conventionally, low pass filters are used for fundamental frequency component detection. Low pass filters introduce a phase lag in the signal. To remove the phase lag, extra lead compensator has to be used. This increases the complexity and cost of the system. Use of PSSR eliminates these problems, as it introduces no delay while detecting the fundamental frequency components. Magnitude and phase plots of second order low pass filter and PSSR are shown in fig.4 and fig.5 respectively.

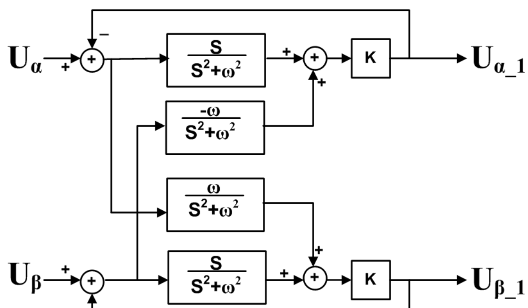

Fig. 3. Schematic diagram of PSSR

The reference $V_{f(abc)}$* are subtracted from the inverter output voltage $V_{f(abc)}$ and the error is processed using a fuzzy logic based voltage controller. Five fuzzy levels, BP (Big Positive), P (Positive), Z (Zero), N (Negative), and BN (Big Negative) are chosen for both the inputs, i.e.; error 'e' and change in error 'de'. Fuzzy rules are formed based on the facts listed below.

i. If the error is high, the controller output should also be high. Else if the error is small, the controller output should be small

ii. If the error is positive and the change in error is also positive, the controller output should be positive. Whereas if both error and change in error are negative, the controller output should be negative

iii. If the error is large positive value, and the change in error is large negative value, controller output should be zero.

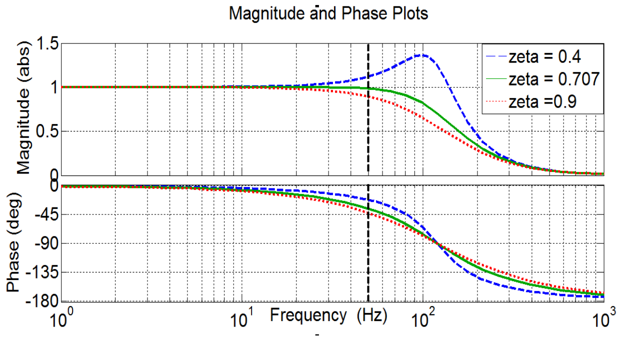

Fig. 4. Magnitude and phase plot of low pass filter

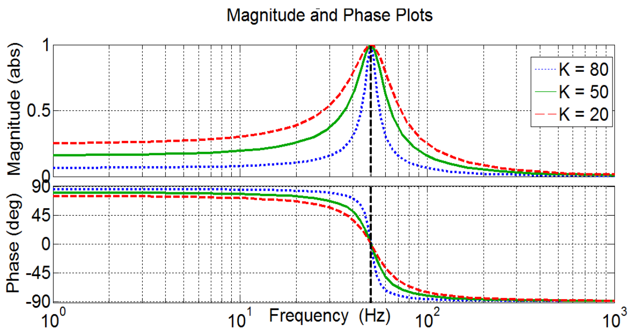

Fig. 5. Magnitude and phase plot of PSSR

Fuzzy rule table is shown in Table 1. Fig.6 shows the normalized input and output membership functions.

TABLE1. FUZZY RULE TABLE

de \ e	**BN**	**N**	**Z**	**P**	**BP**
BN	BN	BN	BN	N	Z
N	BN	BN	N	Z	P
Z	BN	N	Z	P	BP
P	N	Z	P	BP	BP
BP	Z	P	BP	BP	BP

The output of voltage controller is given to a PWM controller to generate switching pulses for the VSI.

III. SIMULATION RESULTS AND DISCUSSION

Numerical simulations are carried out in MATLAB/Simulink environment for different system conditions to verify the effectiveness of the control system. System parameters are listed in Table 2. A three phase programmable voltage source is used as grid. Non-linear load is simulated using a three phase rectifier with an RL load at the dc side. A three phase IGBT inverter is simulated with capacitors and a battery bank at its dc link. A three phase LC filter is connected at the ac side of the inverter. Single phase 1:1 transformers are used as isolation transformers. Primaries of transformers are connected in inverter output, and secondary of transformers are connected in series with the line connecting grid to the load. Different cases considered for simulation are discussed and corresponding results are shown in following section.

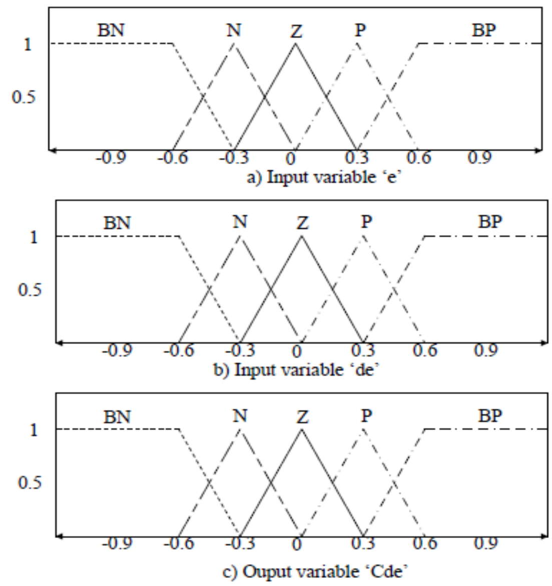

Fig. 6. Normalized input and output membership functions

TABLE2. SYSTEM PARAMETERS

Sl. no	Particulars	Values
1	Supply Voltage	3φ, 415 V, 50 Hz
2	Source Parameters	0.01 mH, 0.1 Ω
3	Load Parameters (3 phase diode bridge rectifier with RL load)	60 mH, 20 Ω
4	DC Link Capacitance	2350 μF
5	DC Link Voltage	700 V
6	Filter Parameters (R, L,C)	0.1 Ω , 0.5 mH, 100 μF

A. Case 1: Single phase sag in grid voltage

A single phase 50 % sag in grid voltage is simulated from 0.1 – 0.3 s by reducing the voltage in 'A' phase to 115 V (RMS) keeping the other phase voltages at 230 V, the rated value. Fig. 7 shows grid voltages in all three phases. Fig. 8 shows the injected voltage in voltages in all three phases in phase with the corresponding grid voltages to compensate the sag. Fig. 9 shows the load voltages in all three phases. It is observed from Fig. 9 that the sag in phase A is compensated within a cycle.

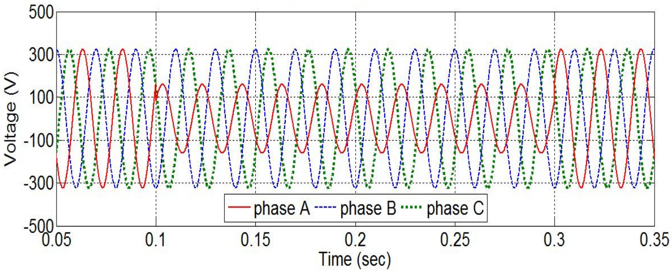

Fig. 7. Three-phase grid voltages in case 1.

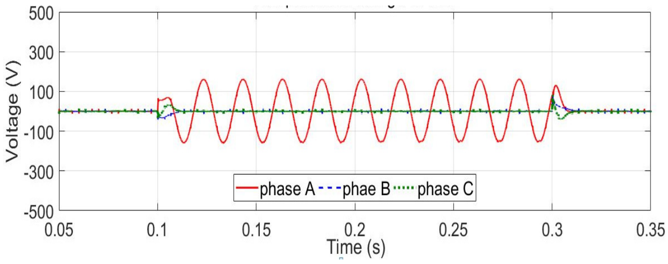

Fig. 8. Three-phase compensating voltages in case 1.

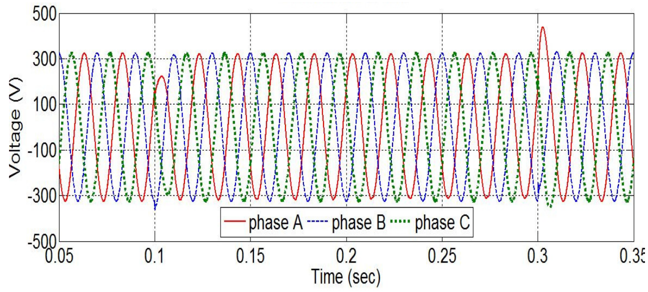

Fig. 9. Three-phase load voltages in case 1.

B. *Case 2: Three phase sag in grid voltage*

A three phase 50 % sag in grid voltage is simulated from 0.1 – 0.3 s by reducing the voltage in all three phases to 115 V (RMS). Fig. 10, 11, 12 shows grid voltages, the injected voltages in phase with the grid voltages to compensate the sag, and the load voltages respectively. It is observed that the sags in all three phases are compensated within a cycle.

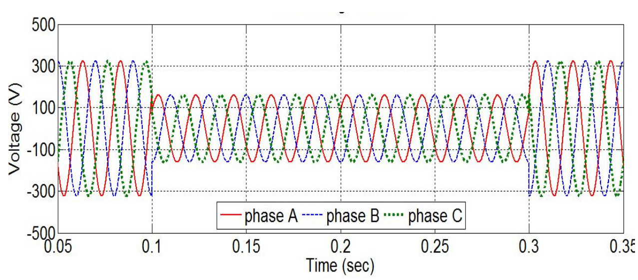

Fig. 10. Three-phase grid voltages in case 2.

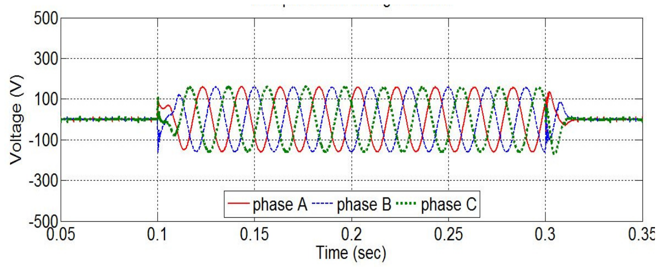

Fig. 11. Three-phase compensating voltages in case 2.

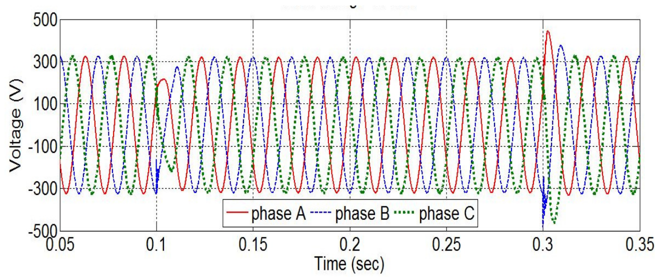

Fig. 12. Three-phase load voltages in case 2.

C. *Case 3: Single phase swell in grid voltage*

A single phase 50 % swell in grid voltage is simulated from 0.1 – 0.3 s by increasing the voltage in phase A to 345 V (RMS) keeping all other phase voltages at 230 V, the rated value. Fig. 13 shows grid voltages. Fig. 14 shows the injected voltages, in phase with the grid voltages to compensate the swell. Fig. 15 shows the load voltages. It is observed that the swell in all three phases are compensated within a cycle.

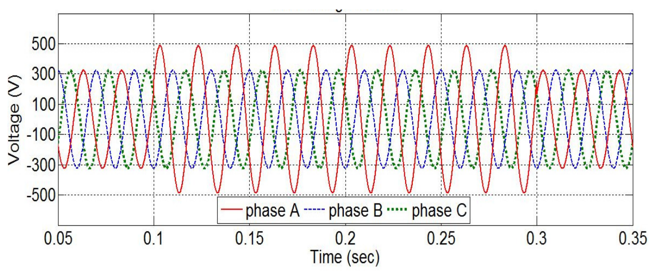

Fig. 13. Three-phase grid voltages in case 3.

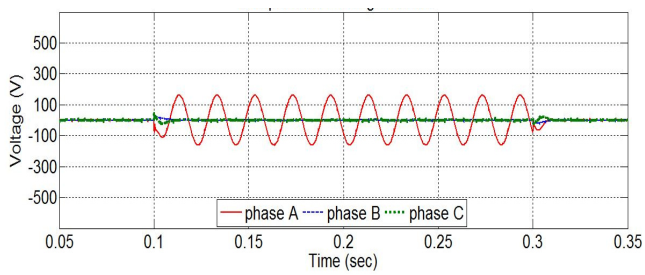

Fig. 14. Three-phase compensating voltages in case 3.

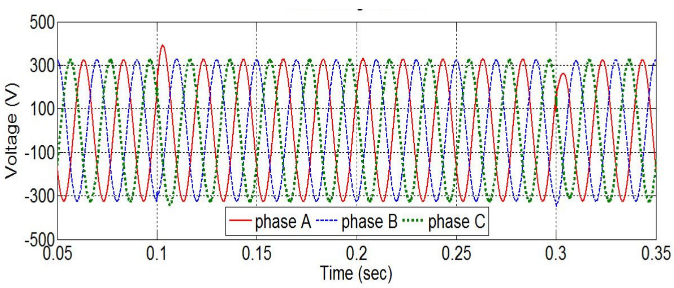

Fig. 15 Three-phase load voltages in case 3.

D. *Case 4: Three phase swell in grid voltage*

A three phase 50 % swell in grid voltage is simulated from 0.1 – 0.3 s by increasing the voltage in all three phases to 345 V (RMS). Fig. 16, 17, 18 shows grid voltages, the injected voltages in phase A, B, C, and the load voltages respectively. It is observed that the swell in all three phases are compensated within a cycle.

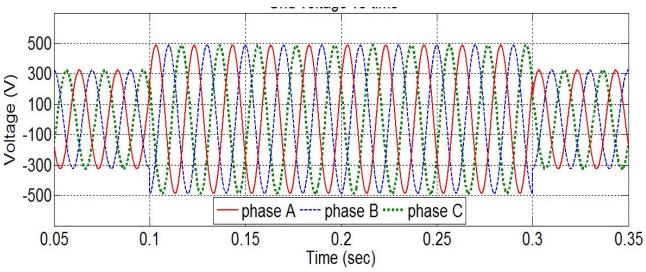

Fig. 16. Three-phase grid voltages in case 4.

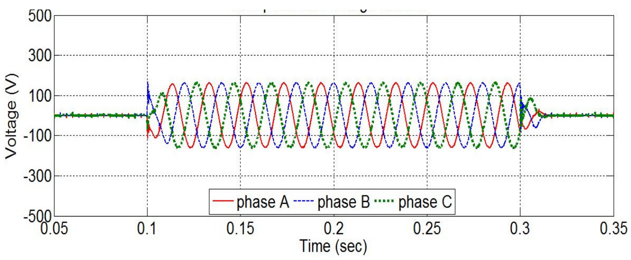

Fig. 17. Three-phase compensating voltages in case 4.

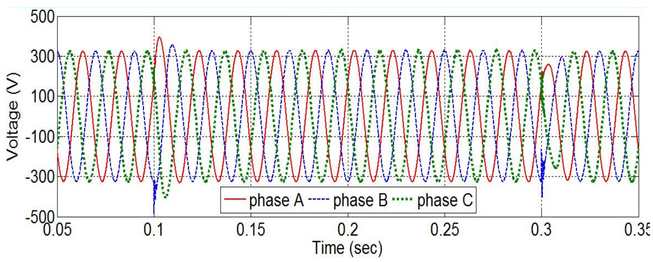

Fig. 18. Three-phase load voltages in case 4.

E. *Case 5: Distortions in grid voltage*

A distorted grid voltage condition is simulated by injecting voltage harmonic components at grid. Fig. 19 shows grid voltages in phase A, at 12.8 % voltage THD (11 % 5th order voltage harmonic component and 6.5 % 7th order voltage harmonic component). Fig. 20 shows the injected voltages in phase with the grid voltages to compensate the harmonics. Fig. 21 shows the load voltages. Fig. 22 and 23 shows grid voltage harmonic spectrum and load voltage harmonic spectrum for phase A respectively. It is observed that the load voltage harmonics is reduced from 12.28 % to 4.68 %. Source voltage harmonic spectra of phase B and C are shown in fig. 24 and 26 respectively. Load voltage harmonic spectra of phase B and C are shown in fig. 25 and 27 respectively. It is observed that in all the phases, the voltage harmonic distortion of load voltages is within the limits as per IEEE standards of power quality [10, 11].

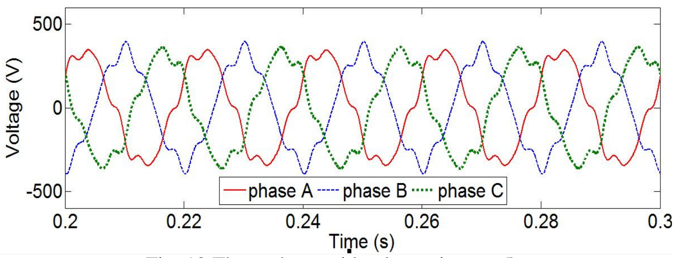

Fig. 19 Three-phase grid voltages in case 5.

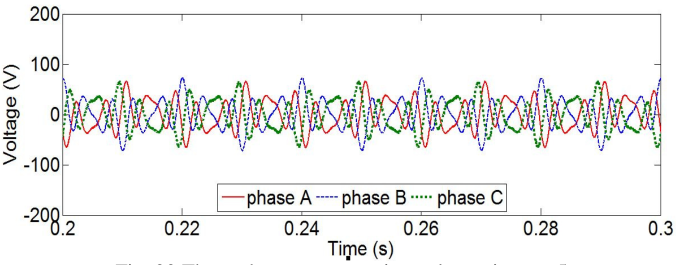

Fig. 20 Three-phase compensating voltages in case 5.

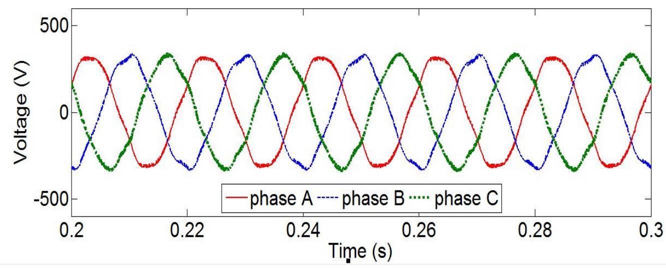

Fig. 21 Three-phase load voltages in case 5.

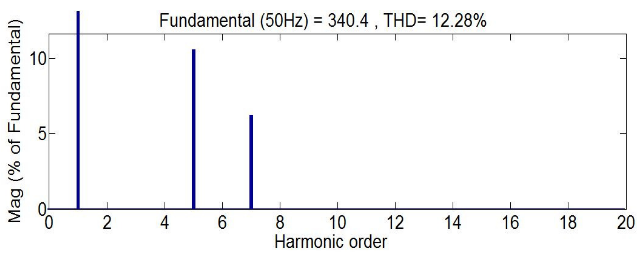

Fig. 22 Harmonic spectrum of grid voltage in phase A in case 5.

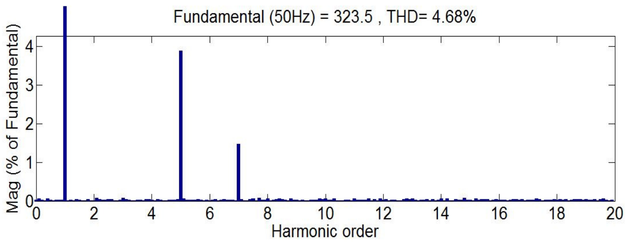

Fig. 23 Harmonic spectrum of load voltage in phase A in case 5.

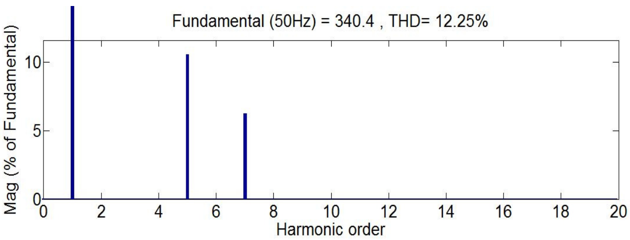

Fig. 24 Harmonic spectrum of grid voltage in phase B in case 5.

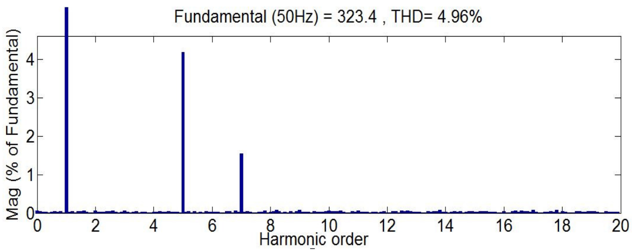

Fig. 25 Harmonic spectrum of grid voltage in phase B in case 5.

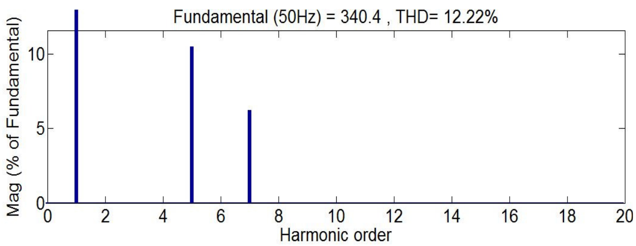

Fig. 26 Harmonic spectrum of grid voltage in phase C in case 5.

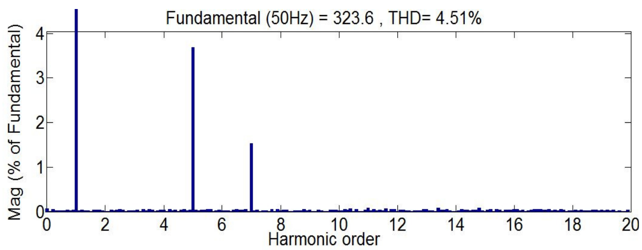

Fig. 27 Harmonic spectrum of grid voltage in phase C in case 5.

Passive filters are used along with active filters if the distortion is high [12]. From the simulation study, it is observed that the performance of series active filter as harmonic voltage compensator is not satisfactory when the grid voltage distortion is more than 13 %. So a shunt passive filter is recommended along with the series active filter.

IV. Conclusion

A fuzzy logic controlled series active filter with load voltage compensation capability has been designed and simulated. Load voltage compensation performance has been enhanced by using a positive sequence sinusoidal regulator. Conventional controllers use low pass filters for calculating fundamental voltage components, which introduces phase delay in compensation voltage, whereas the proposed controller introduces zero phase delay. Fuzzy logic based closed loop voltage controller effectively controls the output ac voltage of voltage source inverter. The simulation studies have been conducted for balanced and unbalanced sag and swell conditions. In all the cases, the series active filter compensation has been found to be effective. The distorted grid voltage condition is simulated, and from the results, it has been concluded that the series active filter effectively compensates the harmonics in voltage, when the grid voltage THD is below 13 %. For THDs more than 13 %, use of passive filters are recommended along with series active filter.

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