Power Quality Enhancement Using Hybrid Power Filter

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ABSTRACT

Modern power electronics devices like active power filter and comprehensive simulation study of relay give the idea of power quality improvement. Generally, in electrical parallel circuits voltage is constant and current is variable parameter, so by using parallel active filter provided variable currents in system and mainly series active filters are used for voltage and power quality improvement and reducing the harmonic content in load voltage. In this paper, FFT analysis is done with help of series active power filter. The results show that proper tune active power filter provides best outputs for the imaginary power compensation and power factor developments. Additionally, the proposed series active filter is used for compensating voltage sag, voltage swell and voltage unbalanced issues in a three-phase distribution system without use of additional devices. The performance of proposed series-active power filter is verified under various voltage related PQ issues by using Matlab-Simulink tool, results are presented.

Keyword: *Power Quality, Passive Filters, Voltage Harmonics, Non-Linear load, Voltage Sag, Voltage Swell, Voltage Unbalance, Total-Harmonic Distortions.*

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1. INTRODUCTION

One of the main responsibilities of a utility system is to supply electric power in the form of sinusoidal and currents with appropriate magnitudes and frequency for the customers at the points of common coupling (PCC). Although the generated voltage of synchronous machines in power plants are nearly sinusoidal ,some undesired conditions such as lightning and short circuit faults and nonlinear loads cause steady state error or transient voltages and current disturbances. For example, electric arc furnaces cause voltage fluctuations, power electronic converters generate current harmonics and distort voltage waveforms, and short circuits faults result in voltage sags and swells [1].

The above-mentioned issues are alleviated by using many ways such as passive and active compensation schemes developed as filtering techniques which includes passive filters and active filters. Passive filters with low circuit arrangement can mitigate harmonics. But passive filters can fix only fixed harmonics for which the particular passive filter is tuned leaving out remaining harmonics in the system. Also as order of harmonics is low, size of the passive filter increases as passive filter parameters are inversely proportional to tuned frequency [2]. On other-hand, Series Active Power Filter (SAPF) injects a voltage component which is connected in series with the supply voltage, thus compensating the voltage harmonics, voltage sags and swells on the load side. The main function of a Series-APF is the protection of sensitive loads from harmonics; short-circuit faults, voltage sags/swells coming from the network.

It mitigates the voltage-related issues like voltage sag-swell, voltage interruptions, and voltage harmonics, etc., in any power system network. It sustains the load-voltage as constant at a defined magnitude and phase quantities attained at PCC point. So as to compensate voltage related issues, Series-APF administers the respective voltage with a suitable phase and magnitude in series with the network/line. Generally, Series-APF neither delivers nor absorbs active power in stand-by mode. Whenever voltage sag and/or voltage swell happens in the network, SAPF provides active power to affected network as delivering/absorbing predominantly to/from battery energy source or DC-link source [3].

Typically, SAPF can be opted for low and/or medium voltage ranges, as well as it is developed as 3-phase 3-wire and 4-wire systems and single phase systems. As usual, the SAPF power-circuitry comprised of DC-AC inverter, DC-link/battery energy source, LC filter units and injection transformer. During voltage sag-swell and/or voltage harmonics, SAPF provides required load power to PCC/load for optimal compensation through DC-link based conditioner, sustains the load-voltage as constant [4]-[6]. The optimal selection and ratings of SAPF topology is totally related with distribution level voltage, investment cost, outage cost, etc.

In this work, FFT analysis is done with help of passive power filter, series active power filter and hybrid power filter. For getting better compensation results, the combination of both passive and active filters are integrated to the line which decreases the over-all ratings of the SAPF device. Additionally, the proposed hybrid active filter is used for compensating voltage sag, voltage swell and voltage unbalanced issues in a three-phase distribution system without use of additional devices. The performance of proposed hybrid- power filter is verified under various voltage related PQ issues by using Matlab-Simulink tool, results are presented.

2. CONVENTIONAL SERIES-ACTIVE POWER FILTER

Conventionally passive L-C filters were used to reduce harmonics and capacitors were employed to improve the power factor of the ac loads [7]-[14]. However, passive filters have the demerits of fixed compensation, large size, and resonance. The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipment, generally known as active filters (AF's) are also called active power line conditioners (APLC's), instantaneous reactive power compensators (IRPC's), active power filters (APF's), and active power quality conditioners (APQC's). Active Power Filters are classified as Series Active power Filter, Shunt Active Filter and Hybrid Active Power Filters (Combination of Series and Shunt Active Power Filters) [15]-[18].

Series active power filters were introduced at the end of 1980. It is usually connected in series with a line through a series transformer. It acts as a controlled voltage source and can compensate all voltage related problem like voltage harmonics, voltage sag, voltage swell, etc. the voltage source converter based series active power filter which are connected at the source side is depicted in Fig.1. The component i, $i_L$and V_{AF} represent source current, load current and injected voltage by the series transformer respectively. Series connected active power filter protect the voltage sensitive devices like super conductive magnetic-energy storage device, semiconductor devices and power system devices from an inadequate supply voltage quality. In many cases series active power filters are used with passive LC filter, where the series active power filter work as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than power distribution system [19]-[22].

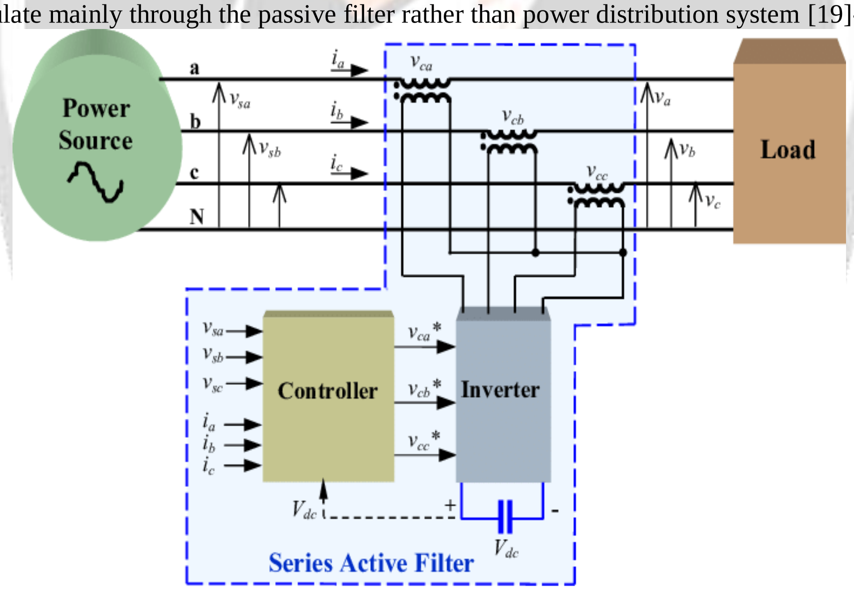


Fig.1 View of Series Active Power Filter

Advantage of this connection is that the rated power of the series active filter is a small fraction of the load KVA rating. However in case of the voltage compensation the apparent power rating of the series active power filter may increase.

3. PROPOSED HYBRID SERIES PASSIVE & ACTIVE POWER FILTERS

A major drawback of active filters is their high rating and associated costs. In addition, a single active filter cannot offer a complete solution for the simultaneous compensation of both voltage and current power quality disturbances. Due to higher ratings and cost considerations, the acceptability of active filters has been limited in practical applications. In response to these factors, different structures of hybrid filters have evolved as a cost-effective solution for the compensation of various issues and more effective in providing complete compensation. Hybrid filters combine a number of passive and/or active filters and their structure may be of series or parallel topology or a combination of the two. They can be installed in single-phase, three-phase three-wire, and three-phase four-wire distorted systems. The passive circuit performs basic filtering action at the dominant harmonic frequencies (e.g., 5th or 7th) whereas the active elements, through precise control, mitigate higher harmonics. This will effectively reduce the overall size and cost of active filtering. The schematic diagram of hybrid power filter is depicted in Fig.2.

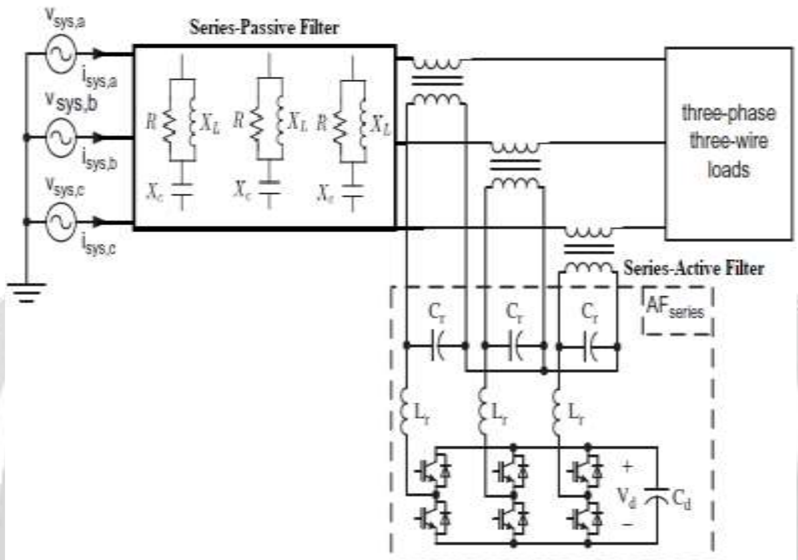


Fig.2 Schematic Diagram of Proposed Hybrid-Series Passive & Active Power Filter

The series-VSI topology of HAPF acts as a controlled voltage source based on PCC voltage which is regulated at a pre-defined value. Although, the series-VSI introduces the required voltage based on the deviation of the PCC voltage from the pre-determined range. The pre-determined PCC voltage values are selected based on the pre-fault/post-fault situation at PCC level. Several control strategies of series-VSI of HAPF is reviewed, in that *abc-to-dq* transformation theory is best suited.

So as to compensate the voltage swell-sag issues, a well-known PWM based control objectives are best suitable for optimal functioning of series-VSI of HAPF. The main theme of the control scheme is to sustain constant voltage amplitude under the voltage interruptions at sensitive load situation. The operation of series-VSI of HAPF is based on the analogy of desired load voltage with respect to actual source voltage. The pertained error is dynamically resolved based on the differentiation of measured and desired value. The actual/measured voltages are transformed into d-q-0 by using Clark's transformation process.

$$(f_{abc})^T = (f_a f_b\, f_c) \tag{1}$$

$$\left(f_{dq0}\right)^T = (f_d f_q f_0) \tag{2}$$

$$f_{dq0} = K_s f_{abc} \tag{3}$$

$$K_s = \frac{2}{3}\begin{bmatrix} cos\theta & cos\left[\theta - \frac{2\pi}{3}\right] & cos\left[\theta + \frac{2\pi}{3}\right] \\ sin\theta & sin\left[\theta - \frac{2\pi}{3}\right] & sin\left[\theta + \frac{2\pi}{3}\right] \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{4}$$

Where,

$$\omega = \frac{d\theta}{dt} \tag{5}$$

It can be expressed as inverse d-q transformation process,

$$K_s = \frac{2}{3}\begin{bmatrix} cos\theta & sin\theta & 1 \\ cos\left[\theta - \frac{2\pi}{3}\right] & sin\left[\theta - \frac{2\pi}{3}\right] & 1 \\ cos\left[\theta + \frac{2\pi}{3}\right] & sin\left[\theta + \frac{2\pi}{3}\right] & 1 \end{bmatrix} \tag{6}$$

The ω angular velocity and the θ is the displacment factor are allied by

$$\theta = \int \omega dt \tag{7}$$

The control scheme of series-VSI of HAPF engages the abc-to-dq0 transformation of actual and refernce voltages. During the symmetrical as well normal situations, the voltage is maintained as constant and the d-frame voltage is maintained as unity (p.u), q-frame voltage is set to zero (0) (p.u, under abnormal situations it may changes). After transformation, both the voltages are sustained like Vd_{act} and Vq_{act} as actual voltages and Vd_{ref} and Vq_{ref} are referrence voltages. The outcome of both actual & referrence voltages are compared by summation point, then some error component is resolved. The error component is minimized by placing the attarctive PI controller; the optimal tuning of proportional (K_p) and integral (K_i) variables by trail-error method is the better way for reduction of error component. The general transfer function of PI controller is shown as below equation,

$$U(s) = k_p + \frac{k_i}{s} E(s) \tag{8}$$

Finally, the error is suppressed by providing the PI controller, the outcome values are V_d^* and V_q^*. The outcome values are the final referrence values which are transformed to regular a-b-c frame by inverse-transformation process.

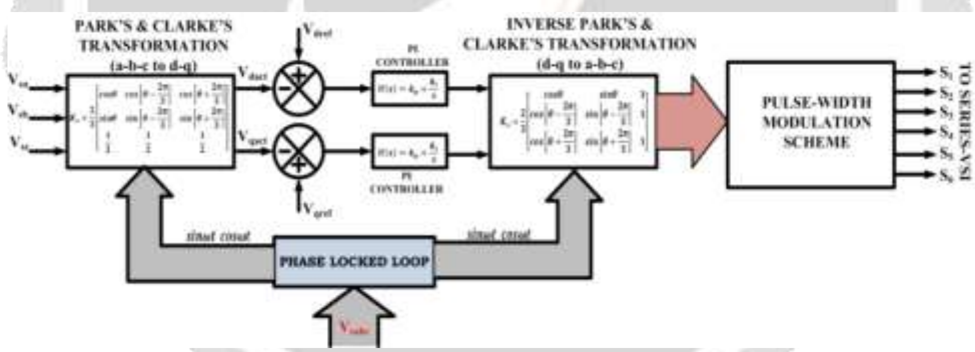


Fig.3 Schematic Diagram of Series-VSI of HAPF Control Scheme

The regular PLL (Phase-Locked Loop) is used to produce the unit-sinusoidal signals which are in-phase with main source voltage. The transformed a-b-c components are used as refernce signal in PWM (Pulse Width Modulation) scheme for generation of optimal switching states to series-PWM of HAPF. The schematic diagram of series-VSI of HAPF control scheme is depicted in Fig.3.

4. MATLAB/SIMULINK RESULTS & ANALYSIS

The Matlab/Simulink modelling is carried based on various cases and the proposed models are developed by using described system specifications illustrated in Table.1.

Table.1 System Specifications

S. No	Parameter	Value
1	Three-Phase Programmable Voltage Source	Vrms-415V, Fs-50Hz
2	Passive Filter	R_{pf}-10Ω, L_{pf}-0.5mH, C_{pf}-550µF
3	Load Impedance	V_L-415, P_L-10KW, Q_L-5KVar
4	DC-Link Capacitor	Vdc-880V, C_{dc}-1500µF
5	Switching Frequency	2000Hz
6	Series Transformer	1:1 Transformer P-4KVA, F-50Hz, R-0.02 Ω, L-0.02mH
7	Line Interfacing Filter	R_f-1Ω, L_f-100 µH

4.1 THREE-PHASE DISTRIBUTION SYSTEM WITHOUT COMPENSATION

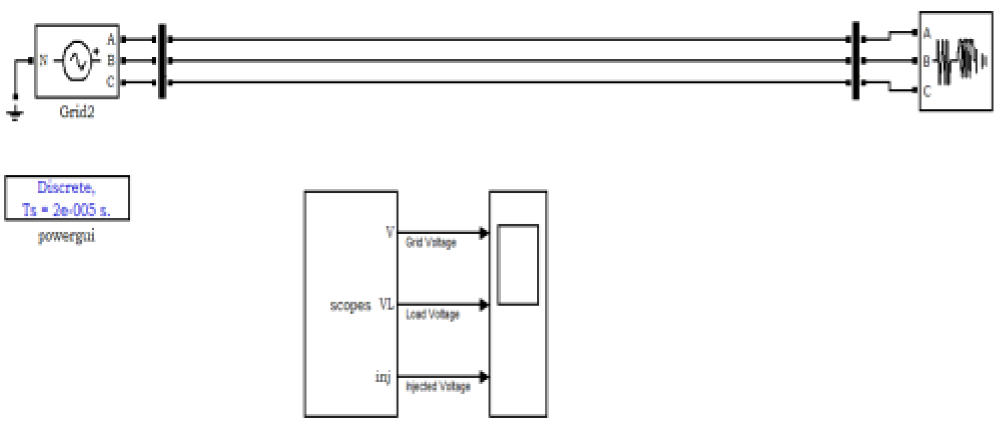
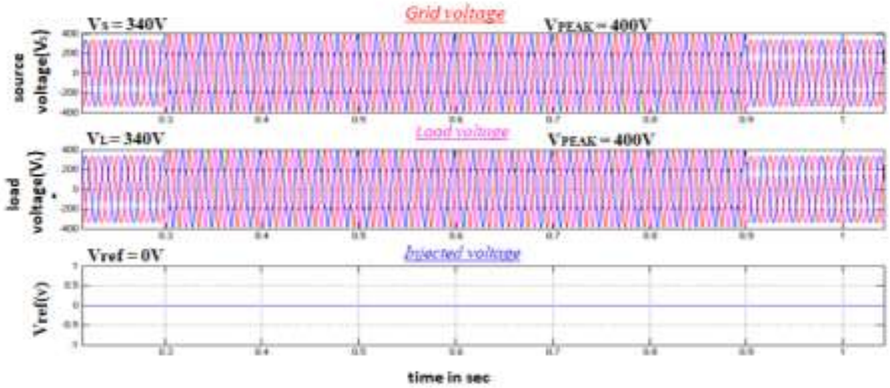


Fig.4 Matlab/Simulink Model of Three-Phase Distribution System Without Compensation



(a) WITHOUT COMPENSATION

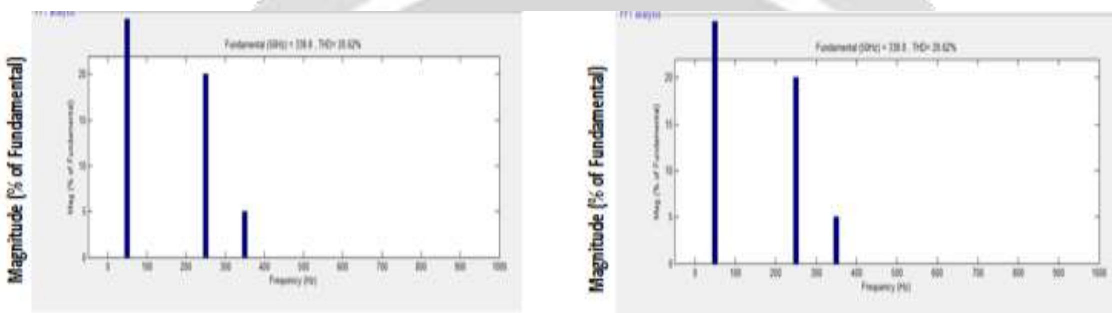


Fig.5 Simulation Results of Three-Phase Distribution System without Compensation

The Matlab/Simulink Model of Three-Phase Distribution System Without Compensation is depicted in Fig.4.The Simulation Results of Three-Phase Distribution System without Compensation is depicted in Fig.5. The three-phase distribution delivers energy to load with a source voltage of 415Vrms, 50Hz supply, due to the harmonic in source voltage at a time of t-0.3 sec to t-0.9 sec. The load voltage voltage also affected due to non-presene of compensator and doesn’t eliminate the voltage harmonics. The THD of source voltage and load voltage is measured as 20.62%, it is uncomply with IEEE standards.

4.2 DESIGN OF CLASSICAL SERIES PASSIVE POWER FILTER FOR HARMONIC COMPENSATION IN THREE-PHASE DISTRIBUTION SYSTEM

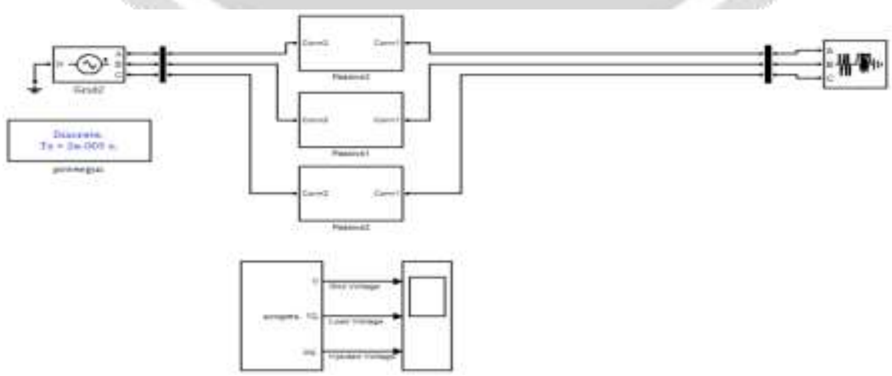


Fig.6 Matlab/Simulink Model of Classical Series Passive Filter for Harmonic Compensation in Three-Phase Distribution System

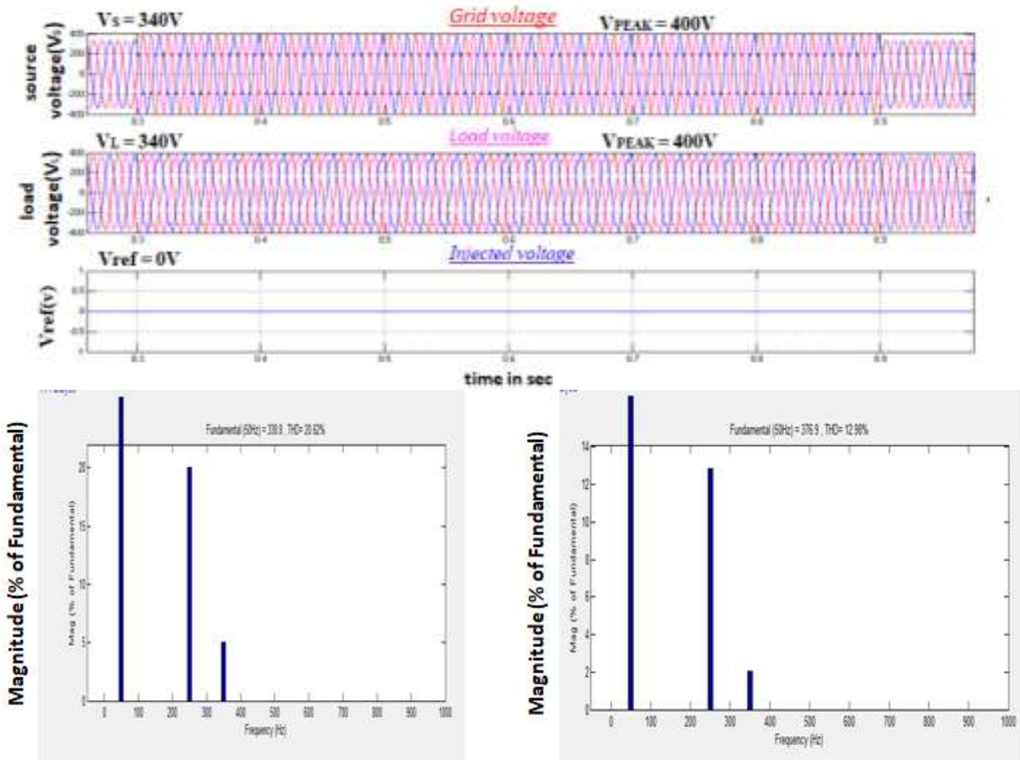


Fig.7 Simulation Results of Classical Series Passive Filter for Harmonic Compensation in Three-Phase Distribution System

The Matlab/Simulink Model of Classical Series Passive Filter for Harmonic Compensation in Three-Phase Distribution System is depicted in Fig.6. Simulation Results of Classical Series Passive Filter for Harmonic Compensation in Three-Phase Distribution System is depicted in Fig.7. The three-phase distribution delivers energy to load with a source voltage of 415Vrms, 50Hz supply, due to the harmonic in source voltage at a time of t-0.3 sec to t-0.9 sec. The load voltage voltage is compensated by using passive filter and eliminates only limited voltage harmonics. The THD of load voltage is measured as 12.98%, it is moderately comply with IEEE standards.

4.3 DESIGN OF PROPOSED SERIES ACTIVE POWER FILTER FOR HARMONIC COMPENSATION IN THREE-PHASE DISTRIBUTION SYSTEM

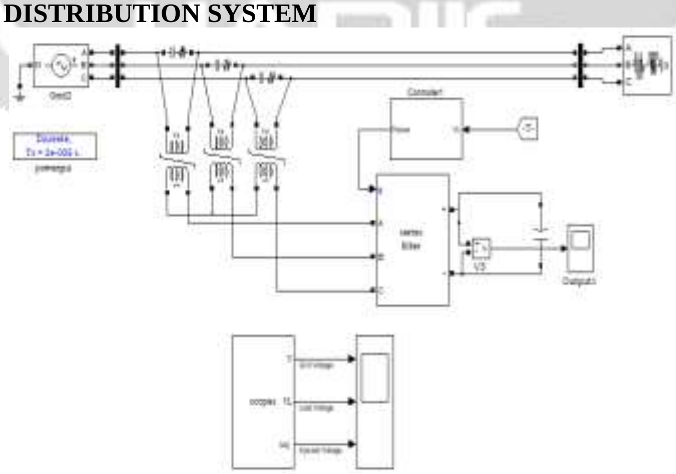


Fig.8 Matlab/Simulink Model of Proposed Series Active Filter for Harmonic Compensation in Three-Phase Distribution System

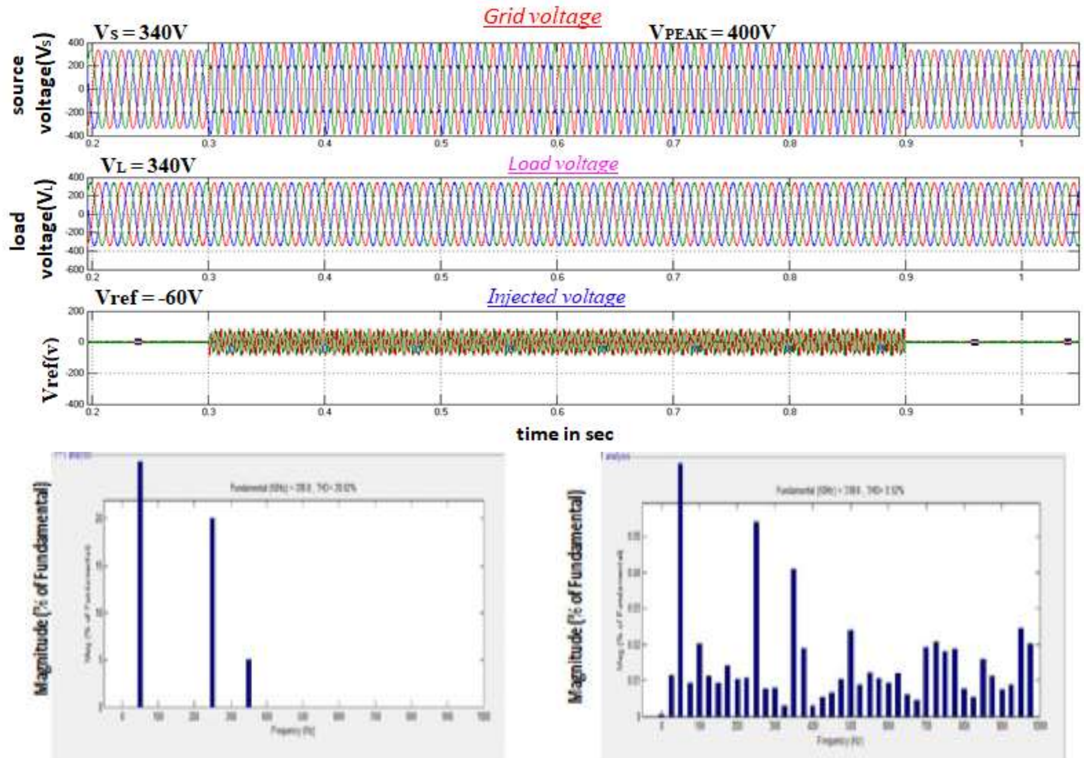


Fig.9 Simulation Results of Proposed Series Active Filter for Harmonic Compensation in Three-Phase Distribution System

The Matlab/Simulink Model of Proposed Series Active Power Filter for Harmonic Compensation in Three-Phase Distribution System is depicted in Fig.8. Simulation Results of Proposed Series Active Power Filter for Harmonic Compensation in Three-Phase Distribution System is depicted in Fig.9. The three-phase distribution delivers energy to load with a source voltage of 415Vrms, 50Hz supply, due to the harmonic in source voltage at a time of t-0.3 sec to t-0.9 sec. The load voltage voltage is compensated by using active series power filter and eliminates voltage harmonics and maintains load as sinusoidal, balanced and linear nature. The THD of source voltage is measured as 20.82% and load voltage is measured as 0.52%, it is comply with IEEE standards.

4.4 DESIGN OF PROPOSED SERIES HYBRID POWER FILTER FOR HARMONIC COMPENSATION IN THREE-PHASE DISTRIBUTION SYSTEM

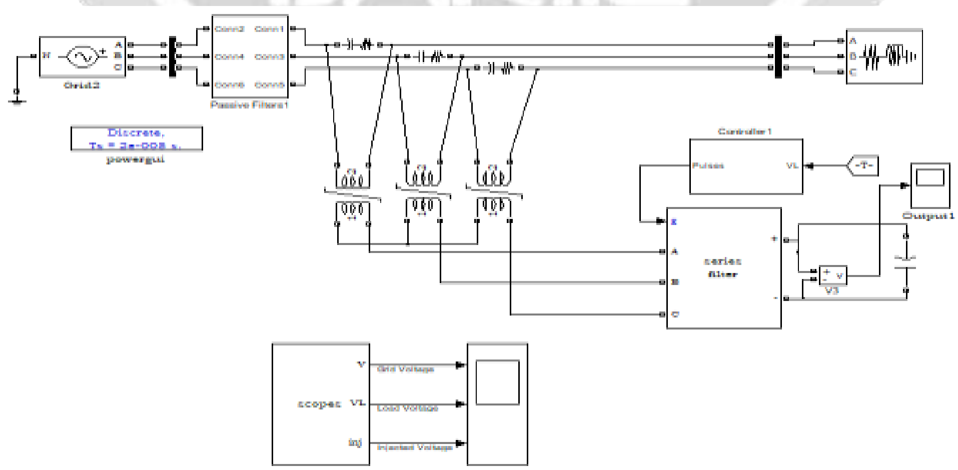


Fig.10 Matlab/Simulink Model of Proposed Series Hybrid Filter for Harmonic Compensation in Three-Phase Distribution System

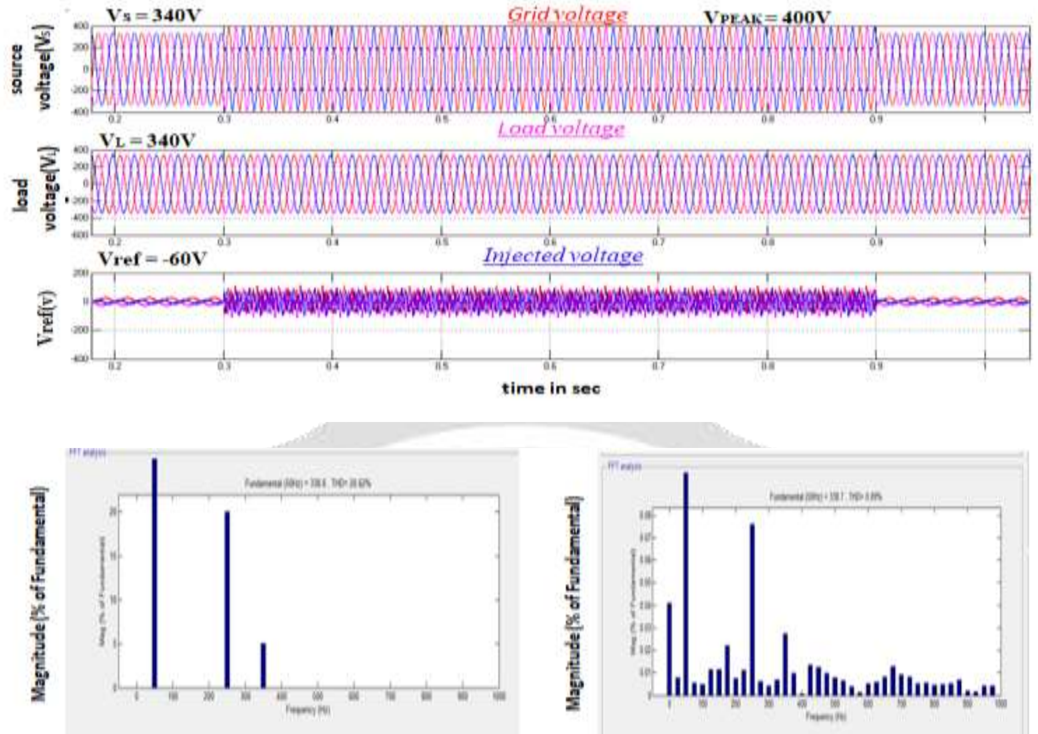


Fig.11 Simulation Results of Proposed Series Hybrid Filter for Harmonic Compensation in Three-Phase Distribution System

The Matlab/Simulink Model of Proposed Series Hybrid Power Filter for Harmonic Compensation in Three-Phase Distribution System is depicted in Fig.10. Simulation Results of Proposed Series Hybrid Power Filter for Harmonic Compensation in Three-Phase Distribution System is depicted in Fig.11. The three-phase distribution delivers energy to load with a source voltage of 415Vrms, 50Hz supply, due to the harmonic in source voltage at a time of t-0.3 sec to t-0.9 sec. The load voltage voltage is compensated by using active series hybrid power filter and eliminates voltage harmonics and maintains load as sinusoidal, balanced and linear nature. The THD of source voltage is measured as 20.82% and load voltage is measured as 0.09%, it is comply with IEEE standards.

Table.2 Comparative Analysis of Various Compensation Schemes for Elimination of Voltage Harmonics in Three-Phase Distribution System

Case I Results

S.No	Conditions of APF	THD%
1	SAPF not activated from 0.3 to 0.9sec	20.62%
2	PAPF activated from 0.3 to 0.9sec	12.98%
3	SAPF activated from 0.3 to 0.9sec	0.52%
4	HF activated from 0.3 to 0.9sec	0.09%

4.5 DESIGN OF PROPOSED SERIES HYBRID POWER FILTER FOR VOLTAGE SAG-SWELL COMPENSATION IN THREE-PHASE DISTRIBUTION SYSTEM

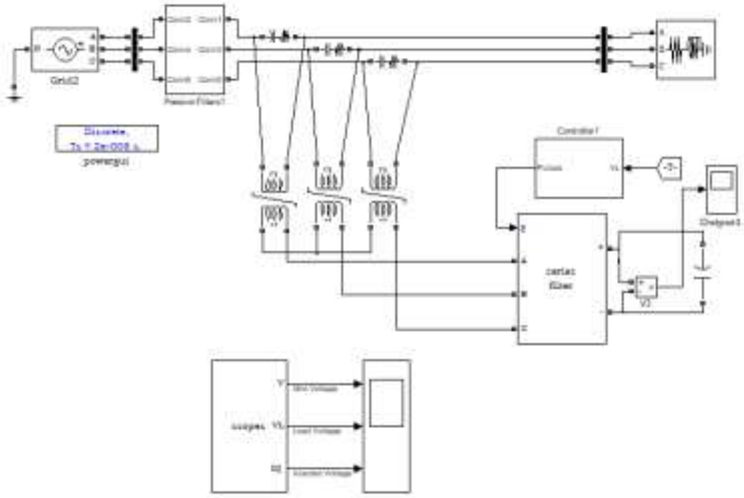


Fig.12 Matlab/Simulink Model of Proposed Series Hybrid Filter for Voltage Sag-Swell Compensation in Three-Phase Distribution System

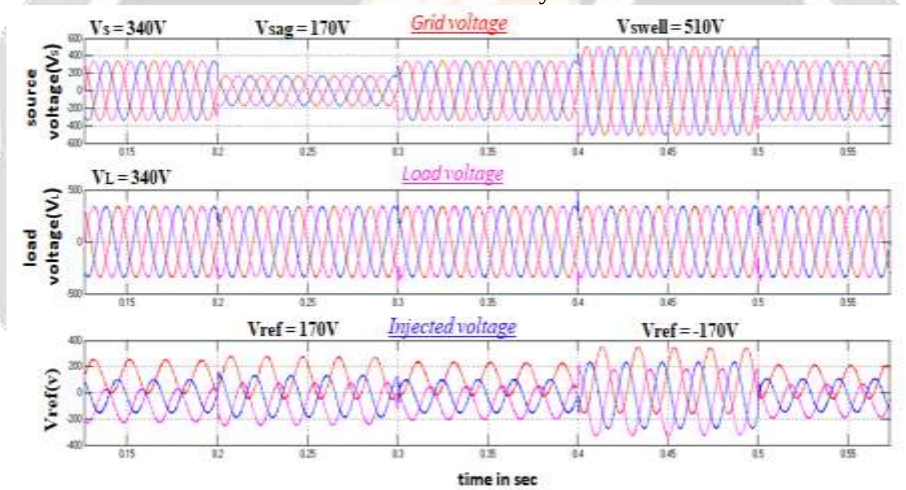


Fig.13 Simulation Results of Proposed Series Hybrid Filter for Voltage Sag-Swell Compensation in Three-Phase Distribution System

The Matlab/Simulink Model of Proposed Series Hybrid Power Filter for Voltage Sag-Swell Compensation in Three-Phase Distribution System is depicted in Fig.12. Simulation Results of Proposed Series Hybrid Power Filter for Voltage Sag-Swell Compensation in Three-Phase Distribution System is depicted in Fig.13. The three-phase distribution delivers energy to load with a source voltage of 415Vrms, 50Hz supply, due to the voltage sag in source voltage at a time of t-0.2 sec to t-0.3 sec and voltage swell in source voltage at a time of t-0.4 sec to t-0.5 sec. During voltage-sag at time t-0.2 sec to t-0.3 sec, the source voltage is decreased with a value of 170V, in this time compensator is injected required voltage as 170V to maintain load voltage as 340V (415Vrms). During voltage-swell at time t-0.4 sec to t-0.5 sec, the source voltage is increased with a value of 510V, in this time compensator is extrcated required voltage as 170V to maintain load voltage as 340V (415Vrms). The load voltage voltage is compensated by using active series hybrid power filter and eliminates voltage sag-swells and maintains load voltage as sinusoidal, balanced and linear nature.

Table.3 Comparative Analysis of Voltage Sag-Swell Compensation in Three-Phase Distribution System

Case II Results

S.NO	CONDITIONS OF POWER QUALITY IN HPF	VOLTAGES
1	Voltage sag ocurred from 0.2 to 0.3sec	V_{Sabc}=170v
2	HPF activated from 0.2 to 0.3sec	V_{Labc}=340v
3	Voltage swell ocurred from 0.4 to 0.5 sec	V_{Sabc}=510v
4	HPF activated from 0.4 to 0.5sec	V_{Labc}=340v

4.6 DESIGN OF PROPOSED SERIES HYBRID POWER FILTER FOR FAULT COMPENSATION IN THREE-PHASE DISTRIBUTION SYSTEM

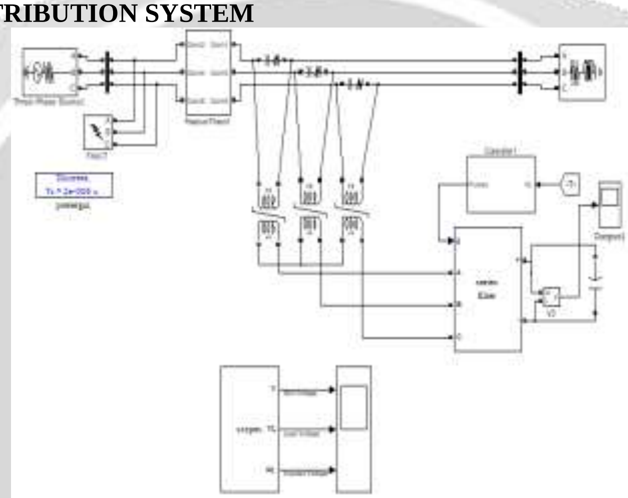
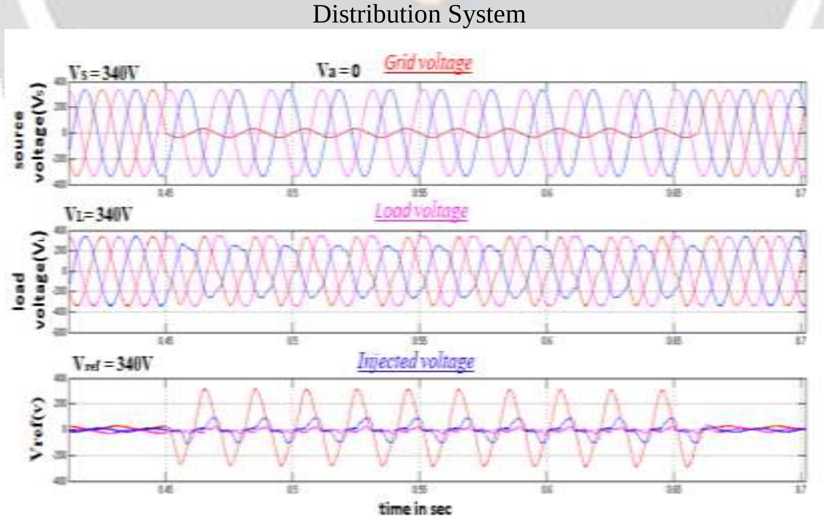
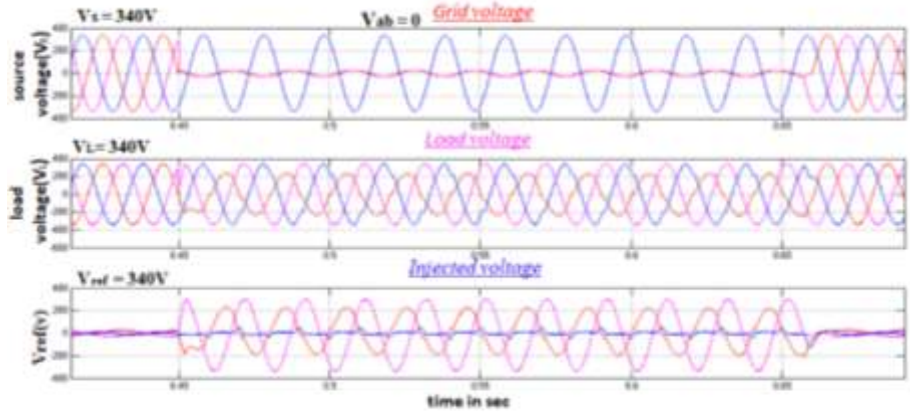


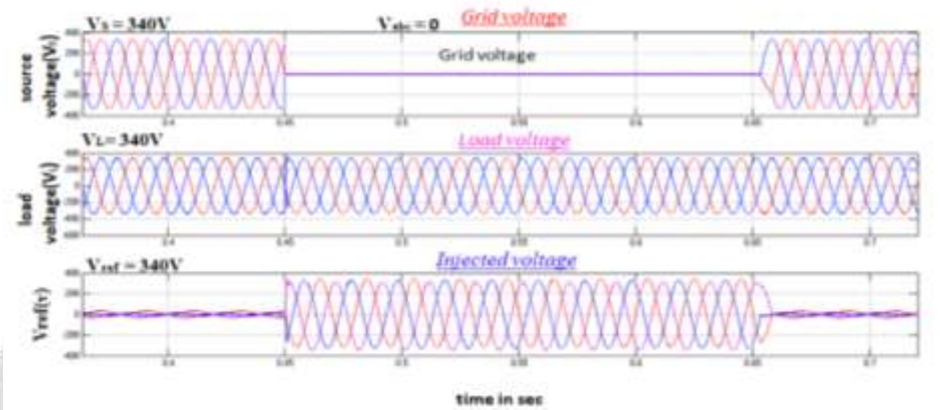
Fig.14 Matlab/Simulink Model of Proposed Series Hybrid Filter for Fault Compensation in Three-Phase Distribution System



(a) LG Fault



(b) LLG Fault



(c) LLLG Fault

Fig.15 Simulation Results of Proposed Series Hybrid Filter for Fault Compensation in Three-Phase Distribution System

The Matlab/Simulink Model of Proposed Series Hybrid Power Filter for Fault Compensation in Three-Phase Distribution System is depicted in Fig.14. Simulation Results of Proposed Series Hybrid Power Filter for Fault Compensation in Three-Phase Distribution System is depicted in Fig.15. The three-phase distribution delivers energy to load with a source voltage of 415Vrms, 50Hz supply, due to the faults in respective phases of source voltage at a time of t-0.45 sec to t-0.65 sec. During faults in respective phases of the source voltage is decreased with a value of 0V, in this time compensator is injected required voltage as 340V to maintain load voltage as 340V (415Vrms). The load voltage voltage is compensated by using active series hybrid power filter and eliminates various LG, LLG and LLLg faults and maintains load voltage as sinusoidal, balanced and linear nature.

Table.4 Comparative Analysis of Various Fault Compensation in Three-Phase Distribution System using Proposed Hybrid Power Filter

Case III Results

LG FAULT

S.NO	FAULT CONDITION	VOLTAGE
1.	Fault ocurred from 0.45 to 0.65sec	$V_{Sa}=0$
2.	Hybrid filter activated during fault condition from o.45 to 0.65sec	$V_{La}=340$

LLG FAULT

S.NO	FAULT CONDITION	VOLTAGE
1.	Fault ocurred from 0.45 to 0.65sec	$V_{Sab}=0$
2.	Hybrid filter activated during fault condition from 0.45 to 0.65sec	$V_{Lab}=340$

LLLG FAULT

S.NO	FAULT CONDITION	VOLTAGE
1.	Fault ocurred from 0.45 to 0.65sec	$V_{Sabc}=0$
2.	Hybrid filter activated during fault condition from o.45 to 0.65sec	$V_{Labc}=340$

5. CONCLUSIONS

The proposed hybrid-power filter is developed for compensation of voltage harmonics, voltage sag-swell, various fault conditions in a three-phase distribution system. By using this hybrid power filter, the load voltage maintained as constant, sinusoidal, balanced and linear nature. By observing the source voltage and load voltage of FFT analysis results shows that harmonics are reduced by using series hybrid filter and observing Fast Fourier Transform (FFT) voltage analysis the percentage THD values contain in load voltage goes to reduces and well within IEEE standards. So, it conclude that series hybrid filters provided better quality power improvements over the individual design of passive and active filter.

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