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SRF-PLL synchronized and Lyapunov based controller for 3-phase shunt active power filter

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Abstract:
Shunt active power filter (SAPF) offers compensation to harmonics generated due to non-linear loads, reactive power and unbalance in the distribution power networks. Due to the broad utilization of non-linear loads have caused current harmonic contamination to the electrical power system.The performance of SAPF depends on the control technique that is used in detection of current components of load that are necessary to be mitigated.In this work a three phase SAPF based on Lyapunov function has been designed for compensation of harmonics generated due to non-linear loads.A control law is determined in the proposed method which makes the derivative of Lyapunov function consistently a negative value for the all stable states.Also to generate a corrective mitigation current,it is important that SAPF should operate in-phase with the operating power system.Hence a proper synchronization technique needs to be integrated when designing the control algorithms of SAPF.So,various types of existing phase synchronization techniques are analyzed and concluded that synchronous reference frame(SRF) based phased locked loop(PLL) is a suitable technique for synchronizing SAPF.Furthermore,the harmonic compensation efficacy of the proposed Lyapunov based SAPF is compared with the one based on the other two conventional approaches.Results are obtained by simulating the SAPF in MATLAB/Simulink,which shows that total harmonic distortion(THD) of source current with Lyapunov based controller is significantly improved than the other two conventional methods.
Keywords: *Active power filter,Lyapunov,Synchronous Reference Frame,PLL*

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I. Introduction:

Theelectricpowerqualityhasbecomeanimportantpartofthedistributionpowersystem.Harmonicsaretheprimarycauseforthepoorpowerquality ofthe distribution system.Harmonics are qualitatively defined as sinusoidal waveforms having frequencies that are integral multiples of the power line frequency. In power system engineering, the term harmonic is widely used to describe the distortion for voltage or current waveforms [1]. In the present scenario, there is an increase in loads that are nonlinear and reactive in nature such as fans, electric pumps, TV, diode rectifier etc. [2]. The aforementioned loads increase reactive power burden and harmonic distortion in the distribution system. Furthermore, with the existence of widespread distributed generations (DGs), the situation from harmonic distortions viewpoint goes extra aggravated on account of harmonic current components injected by DG systems. Generally, the injected harmonic currents deteriorate power quality by increasing total harmonic distortion (THD) of a power system. To compensate reactive power burden and harmonic dis- tortion various custom devices are used such as Shunt active power filter [3], [4], Static Compensator (STATCOM) [5], [6], Distribution Static Shunt Compensator (DSTAT- COM) [7], Dynamic Voltage Restorer (DVR) [8], [9], Passive filter [10], Shunt Hybrid Active filter (SHAF) etc. The harmonic related problem is mitigated by using active power quality conditioner. The active power quality conditioner can be connected in series or parallel and combinations of both (unified power quality conditioners) as well as hybrid configurations [11-14]. The series APLC operates as a voltage regulator and harmonic isolator between the nonlinear load and distribution system. The series active filter injects voltage component in series with the supply voltage and therefore can be regarded as controlled voltage source, compensating voltage sags and swells on the load side. The injected harmonic voltages are added or subtracted, to / from the source voltage to maintain pure sinusoidal voltage across the load. Hybrid APLC is a combination of passive and active power line conditioner.

The hybrid series APLC is controlled to act as harmonic isolator between the source and non-linear load by injection of controlled harmonic voltage source. Unified power quality conditioner is the integration of the series and shunt APLC. The series active power filter has the capability of voltage regulation and harmonic compensation at the utility-consumer point of common coupling. The shunt active power filter absorbs current harmonics, compensate for reactive-power and negative-sequence current, and regulate the dc- link voltage between both active power line conditioners. Power system current harmonics are the major problems in the distribution system, due to widespread use of non-linear loads. From the literature, the shunt active power line conditioner is an attractive choice to solve the current harmonic as well as reactive-power problems. The shunt APLC is compensating harmonic currents drawn by the non-linear loads besides power factor correction.However, due to their inherent weaknesses of inflexibility, instability, and large size, they are soon replaced by active power filters (APFs) which offer versatile solution to harmonic problems [15-18].

A typical SAPF is able to measure degree of harmonic current contamination of a power system and based on that measured data, it generates and injects corrective mitigation currents back into the polluted power system to directly cancel out harmonic currents, thus minimizing severity of harmonic current contamination. This is attainable when all the control techniques applied in its control system are functioning as desired. Nonetheless, many technical issues and challenges remained to be addressed for effective installation of SAPF into the polluted power system. One of the most critical issues is synchronization of the SAPF, where its generated output voltage needs to be properly synchronized with the grid voltage to achieve stable and continuous mitigation operation. The problems will be increasingly difficult when the grid voltage is subjected to faults such as harmonic contamination and unbalanced faults. Failure to synchronize leads to incorrect mitigation and may eventually worsen the harmonic issues which are supposed to be reduced.

Phase synchronization in this aspect can be regarded as a process to minimize phase differences between the output voltage of SAPF and the connected grid voltage and at the same time matching their operating frequency. This process has to be achieved before connecting the SAPF to the designated power system, thereby allowing the power system and the synchronized SAPF to work together.The simulation model is also developed in MATLAB/ Simulink environment. Results of simulations are compared with the other two compensation techniques based SAPF under four different scenarios. Under the first three scenarios, THD is compared among p-q theory [19], SRF method [20] and Lyapunov function based control technique. In the fourth and last case, the enhanced penetration level of renewable energy by Lyapunov function based SAPF is compared with the one based on the other two compensation techniques. The switching pulses are produced by the hysteresis based controller to track the references current. Simulations are performed under various load condition such as a simple nonlinear load with and without utility side voltage distortion, a modified IEEE 13 bus test distribution system loaded with a 3-phase chopper fed direct current (DC) motor drive at a single bus and last especially for increasing the harmonic-constrained penetration level of renewable energy. The achieved results verify the usefulness of SAPF with the Lyapunov function inspired control technique in delivering harmonics compensation under different system scenarios.

II. Shunt Active Power Filter:

The basic principle of active power line conditioner was proposed during 1970s. However, the actual design of active power line conditioner was proposed by Gyugyi and Strycula in 1976 [21]. The shunt APLC often refers to the compensation in the current harmonics and reactive-power. Fig.1 (a) shows the schematic diagram of the shunt active power line conditioner and Fig.1(b) presents the corresponding waveforms of the system. The shunt active power line conditioner compensates current harmonics by injecting equal-but-opposite harmonic components. It operates as current source injecting the harmonic components generated by the load but phase shifted by 1800. As a result, components of harmonic currents in the load current are cancelled by the effect of the shunt APLC and the source current remains sinusoidal and in phase with the respective voltage [22]. This principle is applicable to any type of non-linear load that creates harmonics.

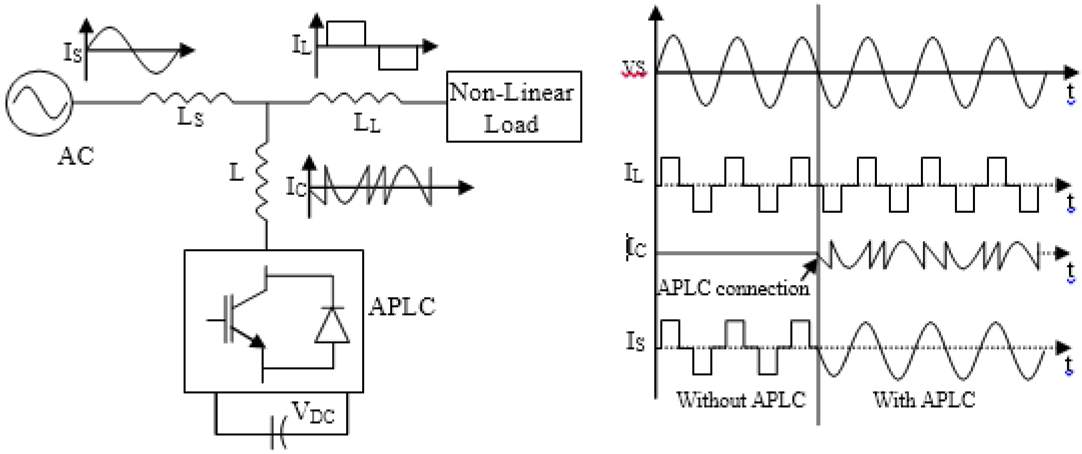


Figure.1(a) Schematicdiagramofshunt APLCsystemand(b)Schematic waveforms

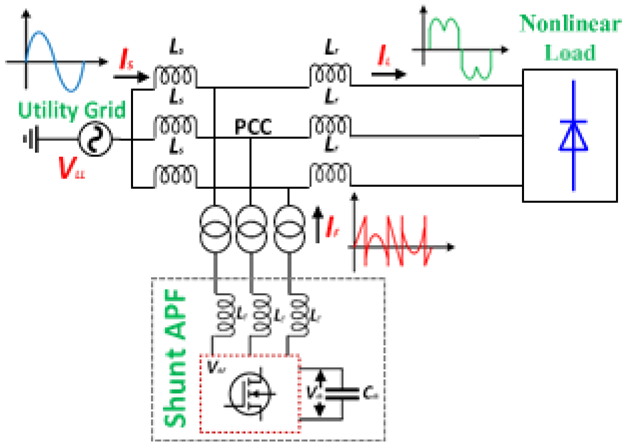


Figure.2BasicdiagramofSAPF

Figure 2 depicts the elementary compensation concept of a SAPF. A SAPF is controlled to either extract or injects a compensating current component IF from/to the point of common coupling (PCC), with the aim of cancelling harmonics and reactive current components from the grid side and thereby sets the source side current a pure sinusoidal one and in line with the phase of source-side voltage.There are different types of topologies for SAPF such as Voltage Source Converter (VSC) using 4-legs, 3-single phase VSC and VSC with 3-legs and a split type of capacitors.

III. LYAPUNOV THEORY BASED CONTROL ALGORITHM

According to the Lyapunov method, SAPF energy reduces along the trajectories of the system. Lyapunov stability theorem conditions that a nonlinear system is universally asymptotically stable in case Lyapunov function V (x) fulfils these properties:

$$\begin{cases} V\,(0) & \\ V\,(x) > 0 & \text{for all x} \neq 0 \\ \dot{V}\,(x) < 0 & \text{for all x} \neq 0 \\ V\,(x) \rightarrow \infty & \text{as } \|\text{x}\| \rightarrow \infty \end{cases}$$

TheLyapunovfunctionforSAPFdefinedasstoredenergyin it and is a positive definite function. Now considering theSAPFmodelshowninfigure2.

$$V_{sa} = L\frac{di_{c1}}{dt} + Ri_{c1} + V_{aP} + V_{PQ} \qquad (1)$$

$$V_{sb} = L\frac{di_{c2}}{dt} + Ri_{c2} + V_{bP} + V_{PQ} \qquad (2)$$

$$V_{sc} = L\frac{di_{c3}}{dt} + Ri_{c3} + V_{cP} + V_{PQ} \qquad (3)$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} \qquad (4)$$

We assume that the source is balanced hence

$$V_{sa} + V_{sb} + V_{sc} = 0 \qquad (5)$$

$$V_{PQ} = -\frac{1}{3}\sum_{n=1}^{3} V_{nP} \qquad (6)$$

Theswitchingfunctionofithlegofthevoltagesourceconverter

$$c_i = \begin{cases} 1 \\ 0 \end{cases} \qquad (7)$$

$$V_{iP} = c_i V_{dc} \qquad (8)$$

IV.PHASE SYNCHRONIZATION TECHNIQUES

This section discusses about the phase synchronization techniques which have so far beenintegrated in the control system of SAPF. It includes the two common techniques in the literaturenamely zero-crossing detection (ZCD) and phase-locked loop (PLL) , and the morerecenttechniquessuchasartificialneural-network(ANN)oradaptivelinearneuron(ADALINE)[,fundamental component extraction , and unit vector generation . In this manuscript,the synchronization techniques are classified according to the intended application of SAPF, i.e.,eitherforsingle-phaseorthree-phasepowersystem, asillustratedinFigure3.Overtheyears, worksonSAPF for three-phase system are more popular compared to single-phase system particularly due towiderapplicationsofpowerelectronicsdevicesandnonlinearloadsinthree-phaseenvironment.However, to avoid redundancy, this manuscript will examine the synchronization technique itself andsubsequently,suitabilityofeachtechniqueforsingle-phaseandthree-phasesystemapplicationswillbehighlighted.

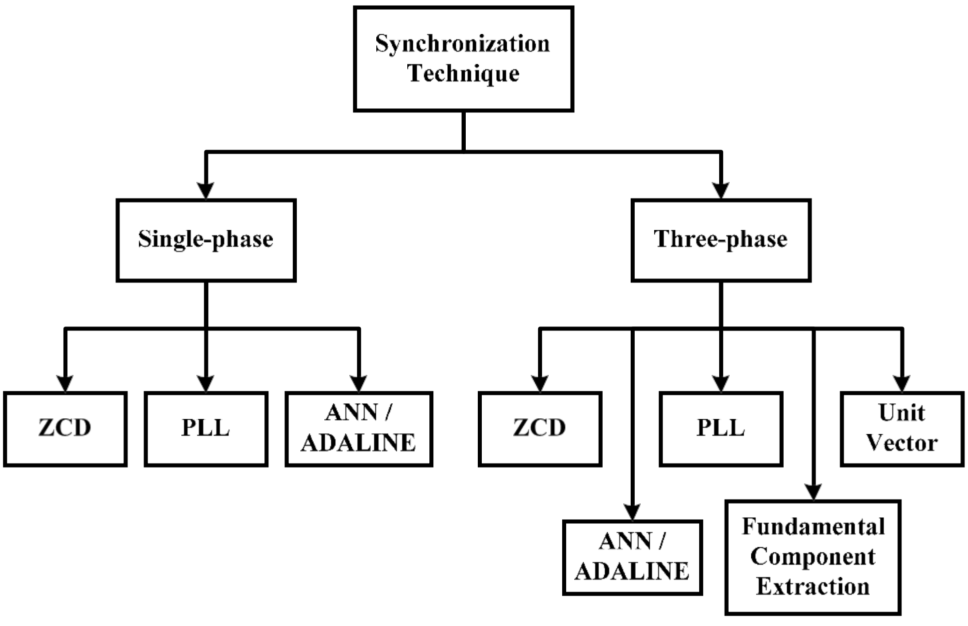


Figure3.OverviewofsynchronizationtechniquesappliedtoSAPF.ZCD:zero-crossingdetection;PLL:phase-lockedloop;ANN:artificialneuralnetwork;ADALINE:adaptivelinearneuron.

Among the five techniques presented in this manuscript, phase-locked loop (PLL) technique isthemostrecognizedandcommonlyappliedapproach,duetoitsuncomplicatedcontrolstructure,and effectiveness in handling various grid conditions.PLL is actually an old technology whichappeared in the literature in the 1930s, and it has successfully been applied over the past decadesinvariousareas,suchasincommunication,controlsystems,andinstrumentation.PLL structure contains three basic functional blocks known asphasedetector(PD),loopfilter(LF),andvoltage-controlledoscillator(VCO),asillustratedinFigure4.In a closed-loop control operation, PD will first compare the two input signals (a reference phasesignal $\theta_{ref}$and a feedback signal θ) and generate a phase error signal $\Delta\theta$. The generated error is thenfiltered by LF (typically a low-pass filter (LPF)) which suppresses noise and other high-frequencyelements from PD. The filtered signal is subsequently processed by VCO to generate an updated outputphase θ which is then feedback to the PD. As the looping process continues, the error generated willcontinuously be reduced and when it reaches zero value, the output phase will be locked and matchesthedesiredreferencephasesignalθ_{ref}.

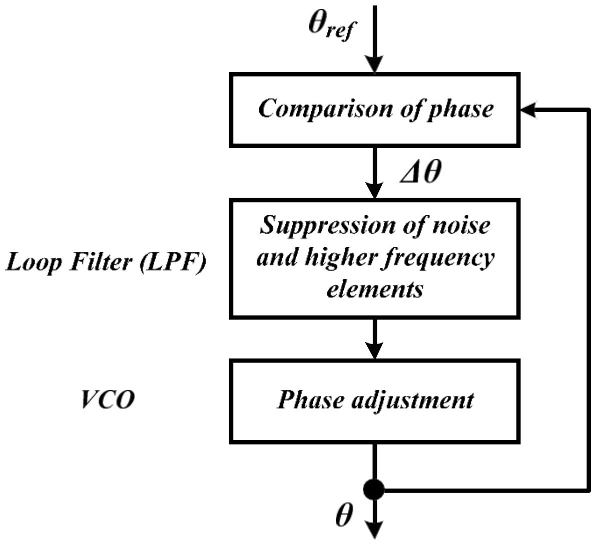


Figure4.Controlstructureofabasicphase-lockedloop(PLL)technique[72].VCO:voltage-controlledoscillator.

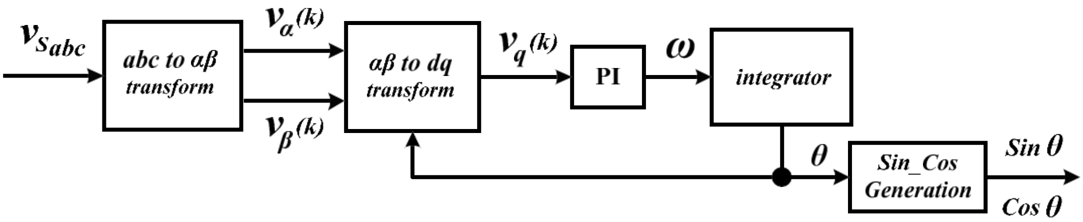
Subsequently, for the application of SAPF, the basic PLL has further been enhanced as synchronousreference frame (SRF)-based PLL (or simply SRF-PLL). SRF-PLL technique has successfullybeenappliedinbothsingle-phaseandthree-phasesystems.Asitsnameimplies,SRF-PLLisatechniquethatutilizesSRFtheoryfortheimplementationofitsPDblock,inwhichthree-phasevoltageinabcnaturalreferenceframeisfirsttransformedintotwo-phase $\alpha\beta$ stationary frame (by means of Clarke-transformation) and then into *dq*rotating referenceframe(bymeansofPark-transformation),asshowninEquations(4)and(5),respectively.Notethatconstant k refers to sampling rate.A proportional-integral (PI) is then applied to manipulate theresulting q variable and eventually the angular frequency ω of the utility will be generated as theoutput. The utility phase angle θ can be obtained by integrating the angular frequency, and the loopingprocess continues by feeding the phase angle back to the $\alpha\beta - dq$transformation block until the phaseangleislockedatafixedvalue.

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

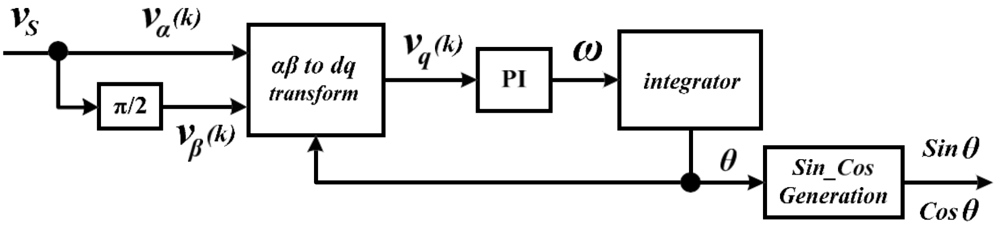
$$\begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} v_\alpha(k) \\ v_\beta(k) \end{bmatrix}$$

SRF-PLLtechniqueisinitiallydevelopedfortheapplicationinthree-phasesystem.However,with a little modification on the initial signal processing approach, it can also be used in single-phasesystem. For single-phase application, there is a need to transform single-phase signal to $\alpha\beta$ stationaryframe by means of other approach due to the facts that Clarke-transformation (the usual transformationapproach) is not applicable in single-phase system. One interesting approach is revealed ,wherethesingle-phasesignalisdirectlytreatedasα framesignalandmeanwhileβ framesignaliscreatedbyintroducingaphasedelayof$\pi/2$totheactualsingle-phasesignal(asillustratedinFigure5b).Thesubsequentphaselockingprocessesforsingle-phaseSRF-PLLisbasicallysimilartothatofthree-phaseSRF-PLL.

ThemainadvantageofSRF-PLLtechniqueisthatitallowsaccurateandquicktrackingofutilityfrequency and phase angle for the case when the source voltage is free from any distortions andunbalances. Unfortunately, it fails to work appropriately when the source voltage is unbalanced and/or distorted due to presence of harmonics.



(a)



(b)

Figure 5.Control structure of synchronous reference frame (SRF)-PLL technique for (a)three-phase and (b) single-phase applications.

One good way to alleviate thisinherent issue is by applying additional low-pass filter (LPF) in the control loop after the $\alpha\beta - dq$transformation block . However, there is a need to carefully match the order and cutting frequencyoftheLPFviaheuristicmanner,toprovidesatisfactorycompromisebetweenitsdistortionrejectionperformance and speed.The good news is that the traditional SRF-PLL has been improved asself-tuningfilter(STF)-basedPLL(orsimplySTF-PLL)anddecoupleddouble(DD)SRF-PLL(or simply DDSRF-PLL) to ensure its effectiveness when it is required to work under unbalancedand/ordistortedutilitygrid.

V. Simulation Results and Discussion

TheperformanceoftheLyapunovFunction-basedControllerof SAPF has been tested under four systems scenarios. Allthe simulations are carried out using MATLAB/Simulinksoftware.ToassesstheperformanceoftheLyapunovFunction-based Controller of SAPF, the system is analyzedbefore and after compensation under all four system scenarios. The specification parameters of the system employedfor analysis under case-1, in the MATLAB simulation, areshowninTable1.Incase-1theproposedSAPFisfirst tested on a two-bus system with a 3-phase rectifier typeload.Also,theutilitysideisalsoassumedfullyfundamental positivesequenceat415VoltRMSlinetolineandfreefromany nonlinearity or unbalance. Accordingly, reference DClink voltage is taken as 700 Volt. The value of the DC-linkcapacitoristakenas2000μF.TheassociatedconstantsofPIcontrollergainsareselectedbyhitandtrialandkeptfixedat 15and0.7respectively.However,thetechnicalspecificationof the system in each of the scenarios is considered quitedifferent.

TABLE1.Value of αversus THD and S.S. response.

Value of α	-3	-1	-0.1
%THD	2.92	4.84	8.42
S.S.Response Time (ina sec)	0.07	0.07	0.5

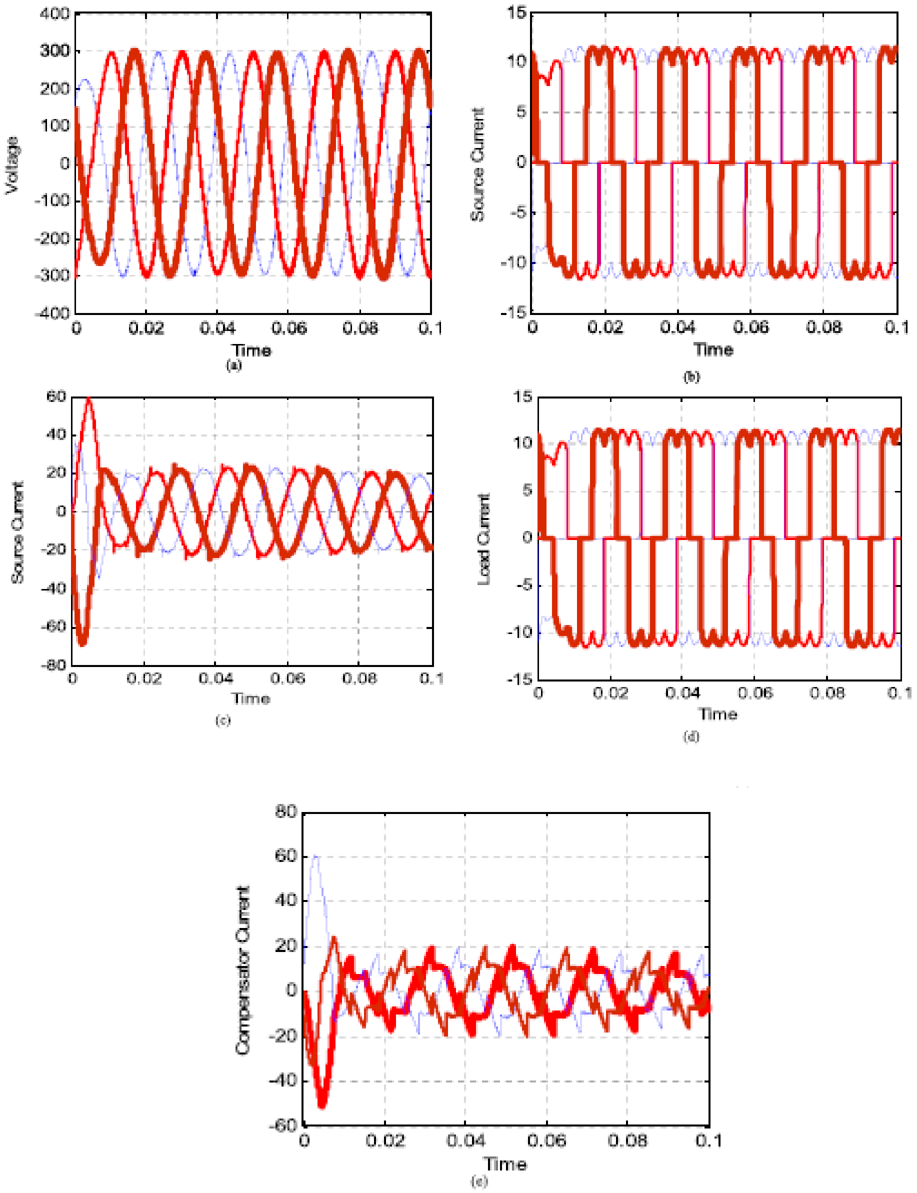


Figure 6. Waveforms of p-q theory (a-b) before and (c-e) after compensation.

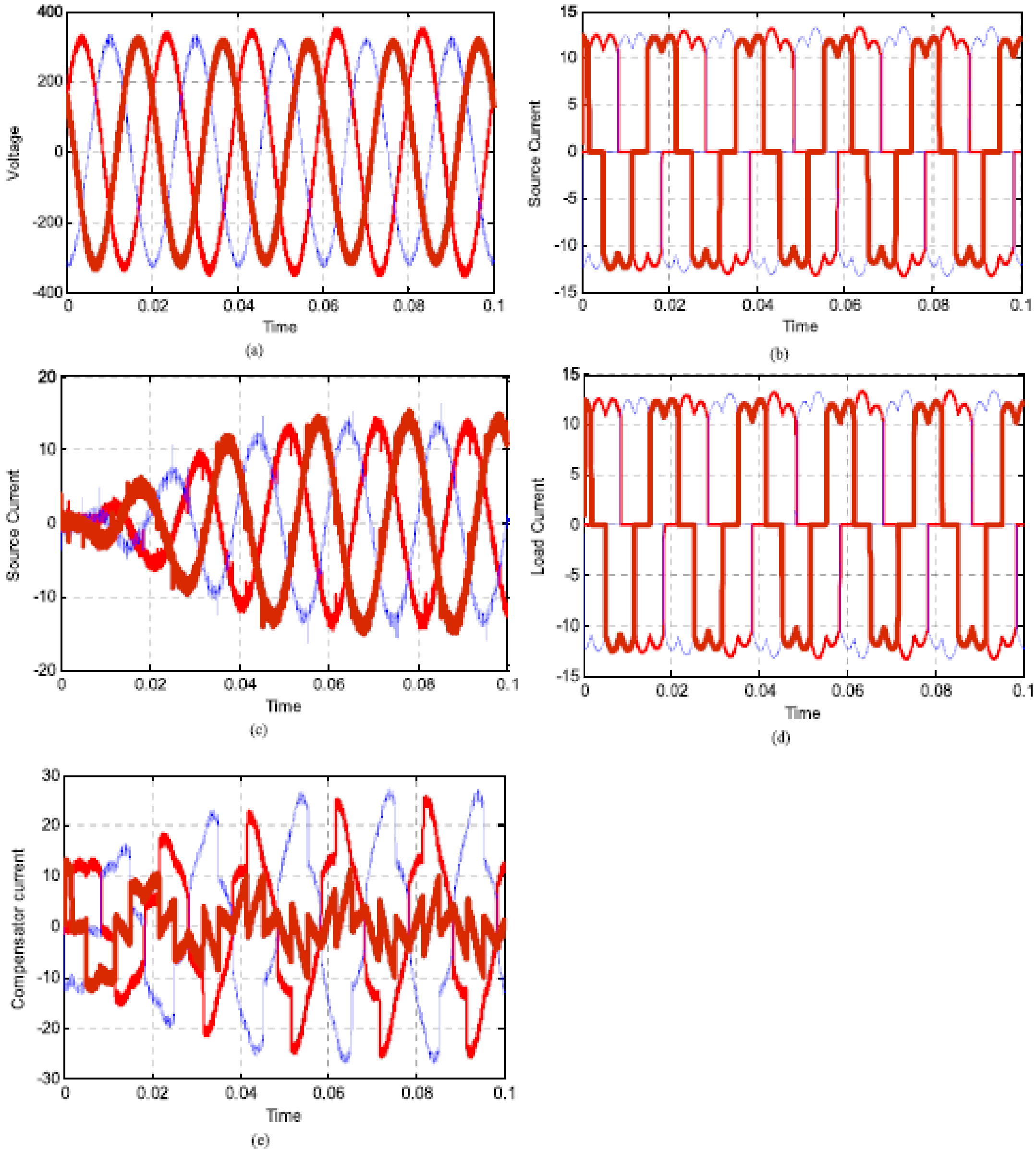


Figure7.WaveformsofSRFtheory(a-b)beforeand(c-e)aftercompensation.

Thewaveformsofthep-qtheoryareshown infigure6(a-e)beforeaswellasaftercompensation.Waveforms6(a-b)belongstothebeforecompensationcase.For an uncompensated system since load current is identicaltothesourcecurrenthenceloadcurrentwaveformhas not been displayed separately. The waveform of thesource or load current clearly depicts the harmonics presentin the same. With the connection of the p-q theory controlled SAPF, the quality of source current waveforms canbeclearlydistinguishedfromtheloadcurrent.However, owing to the limitation of the p-q theory-based controllersourcecurrentisnotclosertothepuresinusoidaloneyetits THD in each phase lies under the limits specified byIEEEStd.519.

Thetransientscanbewitnessedinthesourcecurrentfromtheperiodof0sectoapproximately0.01secespeciallywithp-qtheorycontrolledSAPFalsoformsasignificantbaseof comparison among the three simulated techniques. Oneprobable cause of such transient in the source currents is theslowbuildupofvoltageacrosstheDC-linkcapacitor.

ThewaveformsoftheSRFtheoryaredepictedinfigure 7(a-e) before and after compensation. Because of thestiffnessofthefeederaccordingtotable2,thevoltageat PCC is indistinguishable from that of the source itself.Such scenarios exacerbate the PQ condition in the distribution feeders leading to their de-rating under the presence ofharmonics. Waveforms 7 (a-b) belongs to the before compensation case. Again for an uncompensated system sinceload current is identical to the source current therefore loadcurrentwaveformhasnotbeenpresentedindividually.Wave-forms 7 (c-e) belongs to the after compensation case. Underthe presence of SAPF, the source current waveforms can beclearly differentiated from the load current. Yet due to theimperfection of SRF based controller source current is notcloser to the pure sinusoidal one though it's THD exists underthelimitsspecifiedbyIEEEStd.519.

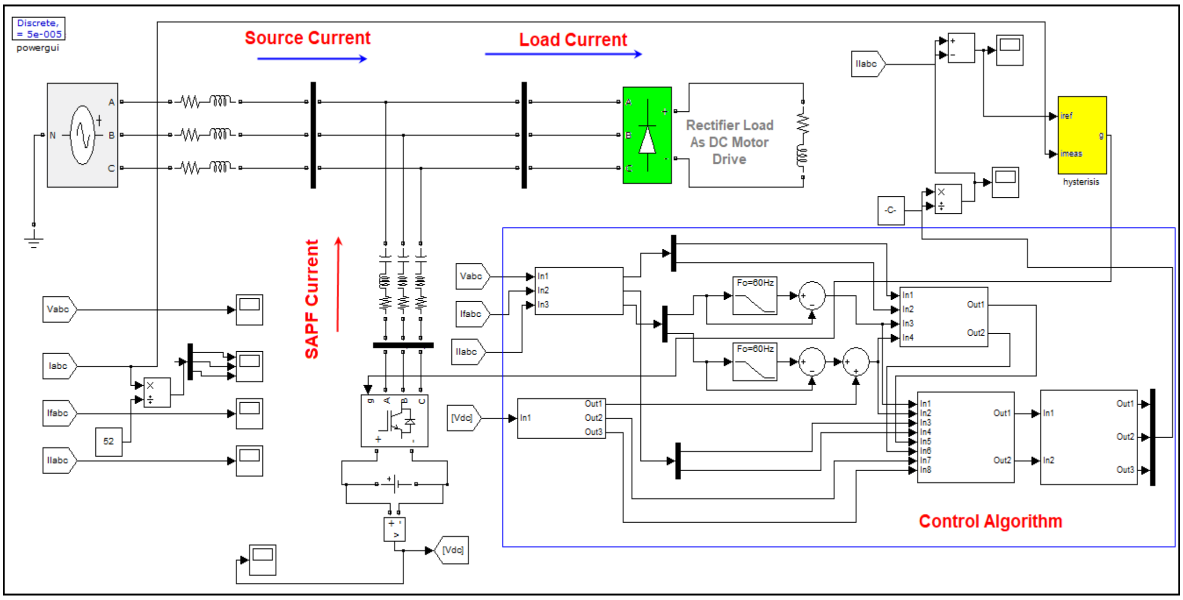


Figure8.Matlab/SimulinkbasedmodelofLyapunovfunctionbasedcontroltechnique[23].

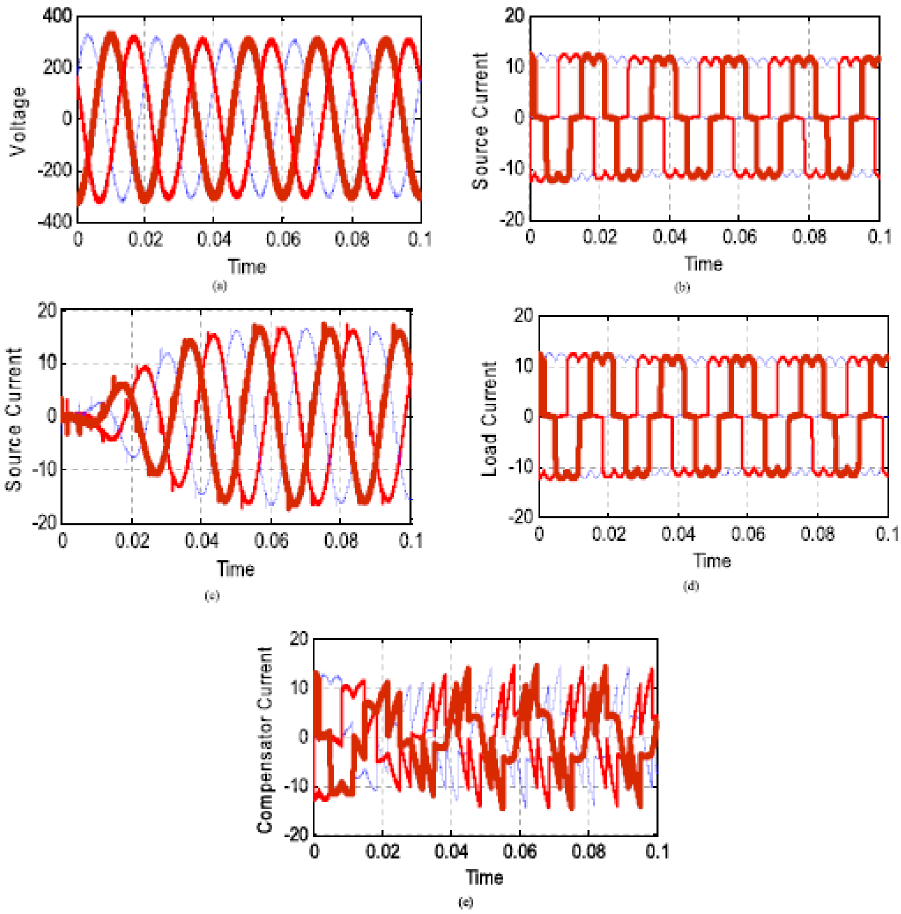
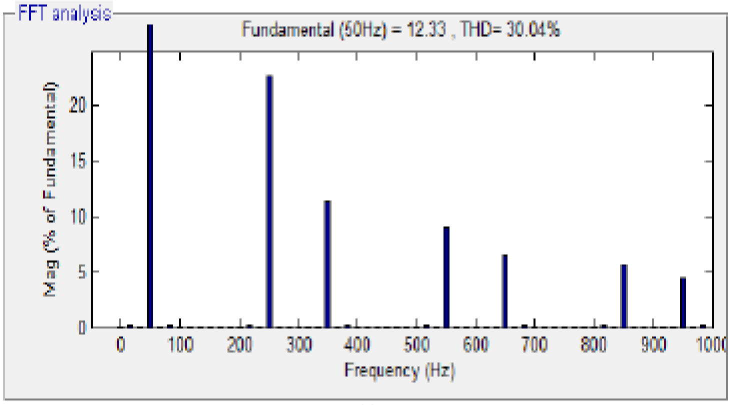
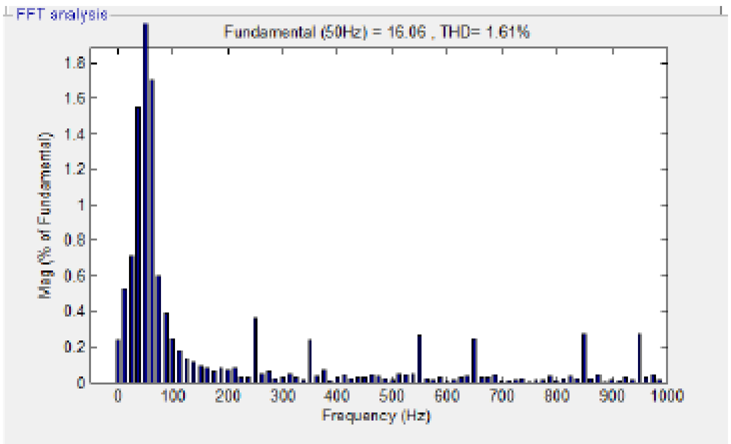


Figure9.WaveformsofLyapunovfunctionbasedcontroltechnique(a-b)beforeand(c-e)aftercompensation



(a)



(b)

Figure10.FFTanalysisa)Beforecompensation,b)Aftercompensation.

Figure 8 depicts the MATLAB/Simulink based model ofLyapunov function inspired control technique for load compensation using SAPF. The waveforms of the Lyapunov func-tion based control technique are shown in figure 9 (a-e)before and after compensation. Waveforms 9(a-b) belongs tothe before compensation case. Again for an uncompensatedsystem since load current is identical to the source currentthereforeloadcurrentwaveformhasnotbeenpresentedindividually. Waveforms 9 (c-e) belongs to the after compensation case. With the connection of the Lyapunov functioncontrolled SAPF, the quality of source current waveformscanbeclearlydistinguishedfromtheloadcurrent.However,againowingtothelimitationofreferencecurrenttrackingofhysteresis loop controller source current is not closer to thepure sinusoidal one yet its THD in each phase lies under thelimits specified by IEEE Std. 519 and better than p-q and SRFtheory.

THD of phase-A of source current, before and after compensation,isdepictedinfigure10.TheTHDofsourcecurrentbytheLyapunovfunctionbasedcontroltechniqueisreducedfrom30.04%to1.61%inphase-a.Whilethesameisreducedfrom 29.18% to 3.19% with the well-known p-q theory andfrom 28.89% to 4.88% with the SRF theory. It becomesevident that the source current with the Lyapunov functionbased SAPF installed at the PCC is rather closer to the desiredpurelysinusoidalone.

Comparing the waveforms of source current i.e. 6(c), 7(c) and 9(c), it can be inferred that the Lyapunov function based control technique offers a better steady-state response. Rise time offered by the Lyapunov function based control technique is also somewhat lessor that the two conventional ones. Figure 6(c) shows the occurrence of high overshoot in the source current in the case of p-q theory. While the same is nearly absent in the response of the other two theories. The little transients can be again witnessed in the source current from the period of 0 sec to approximately 0.01 sec with Lyapunov function based control theory but relatively lesserthan both p-q theory and SRF theory-based controller.Under the second scenario of the system or Case-2, the performance of the proposed Lyapunov function controlled SAPF is tested under utility or source-side disturbances.

VI. CONCLUSION:

Acontrolalgorithm,basedontheLyapunovfunction,ispro-posed for SAPF to mitigate harmonics and reactive powercompensation of nonlinear loads. The performance of SAPFhasbeenfoundsatisfactoryunderallfourcasesofthestudy. The control algorithm is established on the

Lyapunovfunction for achieving global stability in the system. Thesimulationresultsvalidatethecontrolapproachfor SAPF.Ahysteresiscontrollerhasbeenusedtogenerateaswitchingsignal for the voltage source inverter. Based on simulationresults it is clear that all the control algorithm's (p-q theory, SRF theory,Lyapunov function based control theory) performancefound satisfactory i.e. THD is less than 5% accordingtoIEEE519standards. Also underthefullyfundamentalplusbalancedsourcevolt-age and purely nonlinear loading condition Lyapunovfunction-basedcontrolalgorithmgivesthebestperformanceovertheothertwocontrolalgorithmswhicharecommonlyused.The need of a synchronizationalgorithm is dependent on the characteristics of the applied harmonic extraction algorithm.Generally,an explicit synchronization algorithm can be omitted when operation of the applied harmonic extractionalgorithm involves voltage processing stage such as the algorithm developed based on *pq*theory.However, SRF-PLL technique isstill well-accepted due to its uncomplicated control structure. Hence, further enhancements have beenperformedtoimprovecapabilityofSRF-PLLwhichenablesittocopewithdistortedandunbalancedgrid conditions.

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