Performance Evaluation of CSC Based Series APF for Power Quality Improvement

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Abstract

The quality of electric power deteriorates with the ever-growing penetration of power electronics applications in domestic as well as industries including power system operations. The nonlinear characteristics of the power electronics devices and loads are responsible for causing power quality (PQ) problems particularly waveform distortions. Generally, design and implementation of active power filter (APF) to perform PQ improvement task are carried out with the help of voltage source converter (VSC) topology and only a few research literature is available where the current source converter (CSC) topology-based approach is adopted. Through this paper, the performance of a series APF based on the much overlooked CSC topology using synchronous reference frame theory (SRFT) control scheme for mitigating both the load voltage and current waveform distortions in a secondary power distribution system feeding a nonlinear load has been evaluated. The performance of the proposed APF has been investigated by developing a model of the said filter in the MATLAB/SIMULINK. The simulation results under different working conditions are likewise discussed to validate the proposed model.

Keywords: *Current source converter, custom power device, active power filter, SRFT*

1. Introduction

The emergence of ever-growing power electronics based nonlinear loads is causing many challenges in providing good quality power to the end users to the modern electric power distribution system operators. The main factors that lead to PQ problems include forces of nature, faults on transmission or distribution system and also by the electric power consumers whose loads are having nonlinear characteristics. “The PQ problems may be in the form of impulsive and oscillatory transients, short duration voltage variations, long duration voltage variation, voltage imbalance, waveform distortions i.e. harmonics, notching, dc offset, and so on [1]”. In spite of the fact that the PQ problem is also caused by the majority of the issues related with power transmission systems such as forces of nature, individual clients of the power distribution system are also responsible in deteriorating the PQ considerably [2, 3]. In order to resolve the above power quality problems at transmission as well as distribution voltage levels, research work on various types of power electronics based custom power device (CPD) are still going on throughout the world. The advancement of power electronics technology coupled with the emergence of high switching speed, high voltage and current handling capable power semiconductor devices such as IGCT will be a driving force in dealing with the power quality problems effectively in the years to come. The two noteworthy power electronics based systems for alleviating the PQ issues are the flexible AC transmission system

(FACTS) and the CPD. The FACTS devices are meant for transmission voltage level while CPDs are developed for the distribution voltage levels. CPD centres fundamentally around reliability and power quality. Be that as it may, voltage regulation, balancing of voltage and harmonic mitigation may likewise get benefited from this innovation [1-6]. With the objective of enhancing PQ at power distribution systems, the design and implementation of CPDs are done by using VSC topology instead of CSC one due to various reasons as discussed at [1, 6]. However, this trend would be seen changing in the near future where the CSC based CPDs replacing the VSC based ones with the advent of new concepts on power electronics technology and power semiconductor devices. The CSC topology is normally more faults tolerant and reliable than a VSC because of the arrangement of connecting substantially large inductor that restrains the rate of rising of current in case of a fault [1, 3]. Both the voltage and the current waveforms at the output terminals of a CSC are good sinusoids because of the AC side filter capacitors. In a CSC, the capacitor is used as the inherent filter components. The resonance issues caused by the effects of the capacitances and inductances on the AC side can be eliminated via a cautious plan of designing the capacitor based filter circuit and introducing adequate damping with appropriate control techniques [7]. The switching issues observed at the beginning stage of designing the CSC can be overwhelmed by utilizing a tri-level switching plan which has turned into a standard method in the control of CSC. The power losses that take place at the DC link reactor can be minimized effectively by utilizing superconducting materials [7]. With the advent of powerful semiconductor switches such as IGCT, the requirement of connecting diodes in series with the main switching elements of the CSC will be avoided [1]. Among the different kinds of PQ issues referenced over, the waveform distortions caused by the nonlinear loads is viewed as one of the genuine PQ problems. "In order to manage such issues, passive filter, active filter and hybrid filter with shunt and series configurations are generally used [2]". The APFs designed with VSC topology are widely available in most of the literature but very little research work has been accounted for the CSC approach. Consequently, this paper investigates the performance of a CSC based series APF to alleviate the load voltage and current waveform distortions which are caused by the nonlinear load associated with a secondary power distribution system as an initial step. In order to justify the proposed model for its appropriateness in giving enhanced power quality to the electric power customers, the simulation results have been discussed briefly.

Immediately after the introduction section, the paper has been sorted out in an accompanying way: overviews of power quality and waveform distortions, as well as implications of current harmonics on waveform distortions, are explained in Sections 1.1 and 1.2 respectively. Section 2 of the paper describes the APF for harmonics suppression and CSC based series APF. In Section 3, the paper discusses the proposed CSC based series APF and its Control strategy. The model simulation results with discussions are presented in Section 4 and a brief conclusion of the paper is included in Section 5.

1.1. Overview of Power Quality and Waveform Distortions

The appearance of distributed power generation and increasing application of electronic converter based systems and equipment have led to a great impact on drawing the attention of scientists, engineers and researchers in the field of electric PQ worldwide. "The term power quality is concerned with deviations of the voltage from its ideal waveform (voltage quality) and deviations of the current from its ideal waveform (current quality)" [1, 8]. As the harmonics are the main distorting components in the supply voltage and load current waveforms, the term waveform distortions are generally viewed as harmonic distortions [9]. A deviation from the perfect sine wave of power frequency essentially described by the spectral content of the deviation can be characterized as the waveform distortion. DC offset, harmonics, interharmonics, notching and noise are the different kinds of waveform distortions. The existence of a DC current or voltage in an AC power system is known as DC offset. It is generally caused by power electronic converters. The presence of DC current in the AC network can cause transformer core saturation under normal operation thereby heating the transformer and shortening its lifespan. The sinusoidal voltages or currents with frequencies which are integer multiples of the fundamental frequency of the AC supply system intended to work are known as harmonics. Those currents or voltages with frequency components which are not integer multiples of the fundamental frequency of the AC mains supply intended to work are considered as interharmonics. The interharmonic waveform distortions are caused by the operation of induction furnaces, cycloconverters, arcing devices and static frequency converters. Harsh resonances on the power system can be created by the interharmonic currents due to the coincidence of the natural frequencies of the system with the changing interharmonic frequency. This phenomenon leads to incite the power line carrier communication and causes flicker in digital display panels, electric arc lamps, fluorescent lamps etc. The periodic waveform distortion which is occurred during the operation of power electronic converters is known as notching. Current commutation process from one phase to another phase causes this type of distortion. Amid the notching time frame, there is a transitory short circuit between two phases thereby pulling the voltage as near zero as allowed by the impedance of the system. Finally, the undesirable electrical signals having a spectral frequency less than 200 kHz superimposed upon the power system voltage or current in phase conductors or neutral conductors or signal transmission lines can be characterized as the noise. Power electronic switches, operation of switch mode power supply (SMPS) systems, rectifier loads, control circuits, arcing devices and improper grounding are the major basis of causing noise in the power system. This type of distortion leads to a disturbance in the proper functioning of programmable logic controllers and digital computers. The problem of noise can be resolved by deploying filters, power line conditioners and isolation transformers etc. [10].

1.2. Implications of Current Harmonics on Waveform Distortions

The widespread applications of adjustable speed electric motor drives (ASD), power electronics based power supply systems, electronic ballast and battery charging circuits etc. are responsible for causing both the voltage and current waveform distortions on the power distribution system. Such nonlinear loads are the sources of harmonic current in shunt and injecting harmonic currents towards the distribution system at the point of common coupling (PCC).

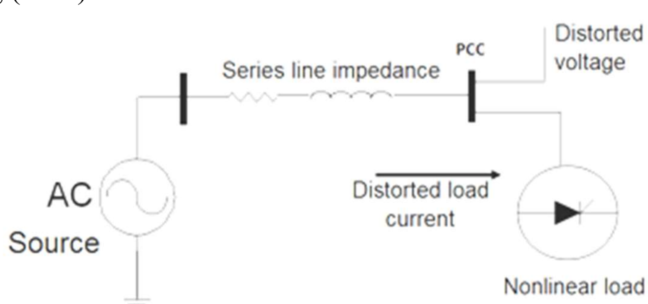

Figure 1. Harmonic currents flowing through system line impedance

Assuming that the source bus voltage is purely sinusoidal as shown in Figure 1; when the distorted currents flow through the linear series impedance of the power distribution system, the phenomenon of voltage distortion occurs. Although the load current harmonics eventually creates the voltage waveform distortions, it ought to be noticed that the load has no control over the voltage waveform distortions [10]. The harmonic currents so developed by the nonlinear loads can act together harmfully with an extensive variety of electrical equipment such as transformers, motors, capacitors etc. thereby triggering extra power losses, reducing their efficiency, overheating and so on. Such harmonic infested currents will able to cause errors in metering instruments of the power distribution system and also may interfere with transmission lines of communication systems [11].

2. Active Power Filter for Harmonics Suppression

The conventional methods adopted for suppressing harmonics are the use of passive and active filters in different configurations viz. shunt, series and hybrid. The hybrid configuration consists of both the passive filter and the APF. The passive filter utilisation is considered to be one of the simplest options for mitigating the harmonic distortions; however, the passive elements such as capacitor, inductor and resistor employed in this method do not always respond correctly to the power system dynamics [12]. In comparison with the passive filter, the active power filter (APF) has many advantageous features. The APF is capable of supplying the current harmonics as well as the reactive currents. The interfacing of APF with the power distribution system does not cause detrimental resonances. Hence, the operating performance of the APF is free from the properties of power distribution systems [10 -12]. The basic role of APFs introduced by the utilities is either for compensating the voltage harmonics and imbalance or to deliver harmonic mitigation all through the power distribution system. The classifications and various configurations of the APFs are discussed at [13].

2.1. CSC based Series APF

The CSC based series APF can be configured as shown in Figure 2. A coupling transformer is utilized to interface the series APF with the power distribution system.

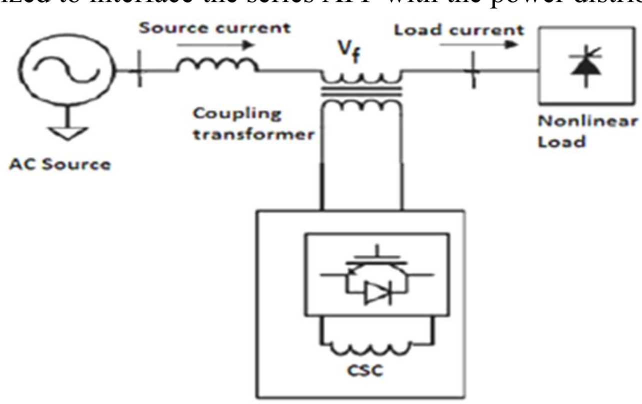

Figure 2. Basic configuration of a CSC based series APF

The CSC sub-block has its own AC side capacitor filter as depicted in Figure 3 and this sub-block act as a controllable current source. For the CSC converter topology, GTO switches which have adequate reverse voltage blocking capacity are preferred. The CSC circuit has been configured in a 3-leg bridge manner by using 6 number of GTO switches as shown in Figure 3.

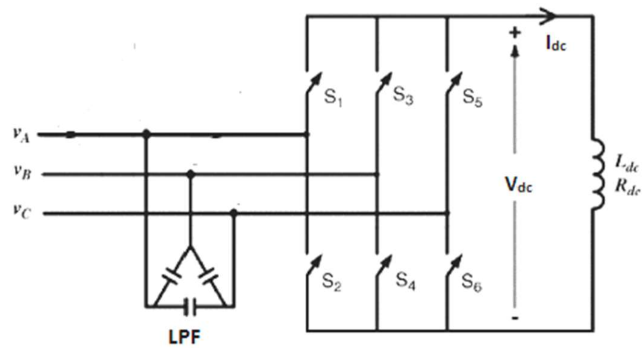

Figure 3. Simplified circuit diagram of CSC

The necessary power supply to this 3-phase bridge inverter circuit is obtained from a DC link reactor represented by L_{DC}. A capacitor based 3-phase low pass filter (LPF) connected in delta configuration is interfaced at the output terminals of the CSC in order to smoothen output waveforms [1]. The process of designing such a filter circuit has been extensively discussed at [14]. From the equivalent circuit diagram of the series APF shown in Figure 4, the operating principle of the filter circuit to compensate the harmonic currents emanating from the nonlinear load can be analyzed.

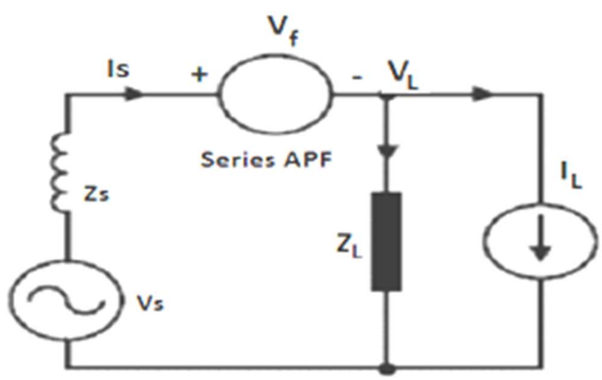

Figure 4. Equivalent circuit of series APF

Here, V_f represents the output voltage of the series APF. Norton's equivalent is represented as the nonlinear load or harmonic current source. When the output voltage of the series APF is regulated as:

$$\boldsymbol{V_f} = \boldsymbol{K} \times \boldsymbol{G} \times \boldsymbol{I_s}$$

(1)

Then, the source current can be obtained from the relation:

$$I_s = \frac{Z_S \times I_L}{Z_S + Z_L + KG} + \frac{V_S}{Z_S + Z_L + KG}$$

(2)

In equations (1) and (2), the equivalent transfer function of a detection circuit of harmonic current with a time delay of the control system is represented by G. The value of G is intended to be equal to zero at the fundamental frequency and approximately equal to 1 for the harmonic components. And K is a gain with the dimension of ohms in per unit [16]. V_{sh} is the distortion voltage harmonics of the AC source and its magnitude is usually much lower than the magnitude of I_{Sh} which is the harmonic current of the harmonic source. If the condition:

$K \gg |Z_L|$ h and $K \gg \left| \frac{Z_S}{Z_L} \right|$ h

(3)

is satisfied, we get

$$V_f \approx Z_L I_{Lh} + V_{Sh} \quad (4)$$

$$\boldsymbol{I_s \approx 0} \quad (5)$$

Thus, the source current becomes sinusoidal. The equation (3) is the necessary working condition for the series APF to compensate the harmonic components of the current source. Equations (4) and (5) demonstrate that neither the distortion source voltage harmonics, V_{Sh} shall show up on the load side nor the load harmonics current, I_{Lh} will flow towards the AC source [16].

3. Proposed CSC based Series APF Model

As depicted in Figure 5, the arrangement of series APF is alike to that of the shunt APF with the exception that the interfacing inductor has been replaced by a coupling transformer which is connected in series with the power distribution system. The segregation of the harmonics between the nonlinear load and the source is the basis for operating the series APF.

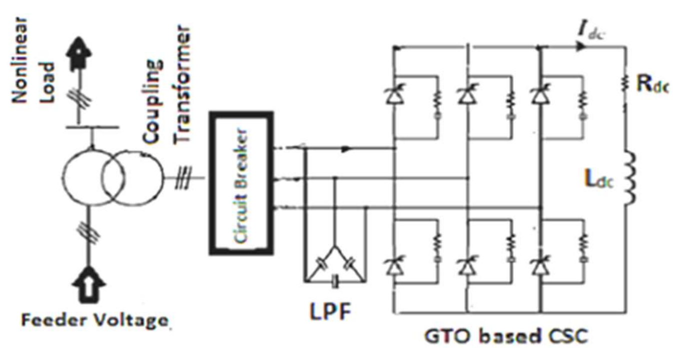

Figure 5. Schematic circuit diagram of the proposed series APF

The seclusion process should be possible by infusing harmonic voltage through the coupling transformer. In order to ensure a pure sinusoidal voltage waveform across the nonlinear load, the injected voltages are added or subtracted to or from the source voltages. The series APF has been controlled in such a manner that this offers zero impedance for the fundamental frequency portion; however, for the harmonic frequency components, it shows up as a resistor with high impedance.

Subsequently, the current harmonics are restricted to flow out from the nonlinear load to source and the other way around [11]. As the DC link circuit in the CSC topology comprises just an inductor with its internal resistance, the time constant will be high and consequently influences the design procedure of the circuit. We can express the time constant for the DC link reactor as:

$$\tau_{dc}=\frac{L_{dc}}{R_{dc}} \qquad (6)$$

Along these lines, the estimation of L_{dc} ought to be chosen as little as feasible for permitting quick rise or decay of the average value of DC link reactor current [1, 14-15].

3.1. Model Control Strategy

In order to achieve a good sinusoidal AC voltage waveform across the nonlinear load at PCC, generation of appropriate gate drive signals for the GTOs of the converter circuit is quite essential [1, 17]. For this purpose, a control scheme based on the proportional integral (PI) controller has been developed as shown in Figure 6.

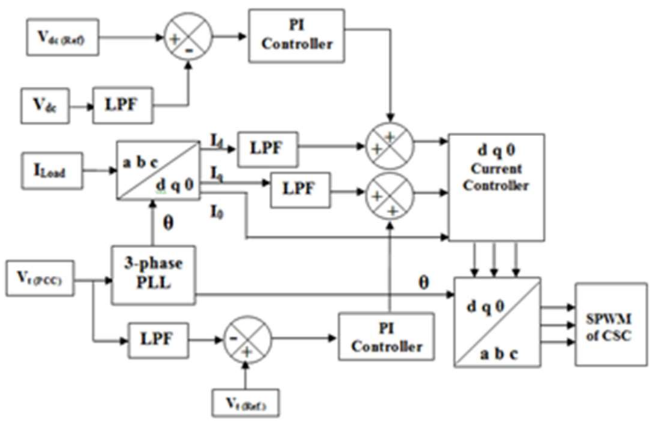

Figure 6. Control system block diagram of the series APF

The constant switching frequency capable modulation technique which is known as sinusoidal pulse width modulation (SPWM) has been chosen for the proposed model. The adoption of the switching strategy shall decrease the pressure on the GTOs deployed in the CSC circuit [18]. This control methodology ensures to provide the desired AC voltage profile in terms of its magnitude and waveform characteristics i. e. sinusoidal to the PCC at which the nonlinear load is connected. The SPWM based switching strategy is simple and provides better responses. Since the secondary power distribution system works at a moderately low voltage and power levels, this strategy offers a more adaptable choice than that of the fundamental frequency switching scheme [1, 2]. The proper functioning of the series APF is guaranteed by the reference signals to be processed in the controller. The estimation of the reference signal is started with the detection of necessary voltage or current signals for gathering precise system variable data [11]. In most of the custom power (CP) controllers, the commonly used control schemes for the purpose of generating of reference source currents include synchronous reference frame theory (SRFT), instantaneous reactive power theory (IRPT), instantaneous symmetrical components based and unity power factor (UPF) based etc. [1, 18]. SRFT comes under the time domain reference signal estimation method. This method has the merits of giving a quick response to dynamic operations in the power distribution system and furthermore simple to execute and has a little computational difficulty [19]. For the proposed series APF, the SRFT control method is selected. The SRFT depends on the Park's conversion for changing over the three-phase voltages or currents into their equivalent synchronous rotating frames. In this transformation process, the direct and quadrature components represent the real and reactive components of the three-phase system respectively. The fundamental components are converted into dc quantities and these are segregated by utilising a low pass filter [11]. The proposed control scheme measures only the voltage (RMS) at the PCC and reactive power measurement is not performed. For the series APF, load currents (I_{Load}), the voltage at the PCC, $V_{t\,(PCC)}$ and the DC link reactor voltage (V_{dc}) are sensed and these have been utilised as the feedback signals in the controller. By using the Park's transformation method, the load currents in *abc* frame have been converted into their equivalent *αβ0* frames as given in equations (7), (8) and (9).

$$i_d = \frac{2}{3}\left[i_a \sin\theta + i_b \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad (7)$$

$$i_q = \frac{2}{3}\left[i_a \cos\theta + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \quad (8)$$

$$i_0 = \frac{1}{3}\left[i_a + i_b + i_c\right] \quad (9)$$

A three phase-locked loop (PLL) has been used to provide the necessary cos θ and sin θ parameters. The PLL in the control system gets a signal from PCC, $V_{t(PCC)}$ so as to produce fundamental unit vectors for transforming the detected currents into their equivalent *dq0* reference frame. The DC quantities are extracted by the SRFT controller with the help of an LPF and also the harmonics can be isolated from the reference signals [1, 17]. The terminal voltage at the feeder, $V_{t(PCC)}$ has been regulated through a PI controller after comparing it with a reference voltage $V_{t(Ref.)}$. This process leads to the production of an i_q signal and then it is added with the i_q available at equation (8). The outcome of this summation works as a reference component for the current controller. Another PI controller has been utilised to control the DC link reactor voltage, V_{dc} by processing the error signal so generated after comparing V_{dc} with a reference DC voltage, $V_{dc(Ref.)}$. This step leads to the production of the current component, i_d. The i_d value available at equation (7) is now added with this current. As discussed at [20], the reference source current must be in phase with $V_{t(PCC)}$ and without zero sequence component and this can be generated with the help of inverse Park's transformation. After comparing the sensed currents with the reference source currents, a proportional controller has been utilized to amplify the current error in each phase in the current controller subsection. Now, the SPWM will able to render the required gate drive signals for the GTOs employed in the bridge converter circuit of the series APF.

4. Model simulation results with discussions

Figure 7 shows the proposed Simulink model of the CSC based series APF. The secondary power distribution system is connected with a three-phase uncontrolled bridge rectifier which represents as the nonlinear load.

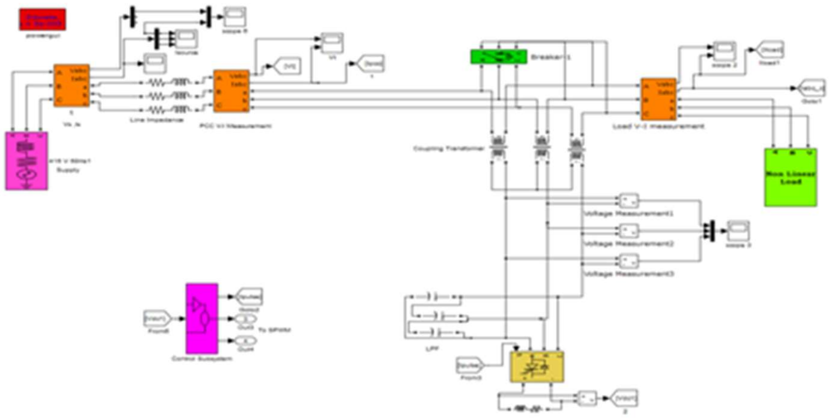

Figure 7. Proposed CSC based series APF in the Simulink model

The parameter settings employed for simulating the proposed model in Matlab/Simulink environment is given in Table 1.

Table 1. Parameter settings

Name of the parameters	Parameter values
Feeder system voltage	$V_{t\,(PCC)}$ = 415 V(RMS), 50Hz
Feeder impedance	R_f = 0.01Ω, L_f = 2mH
Feeder system reference voltage	$V_{t\,(Ref.)}$ = 400 V(RMS), 50Hz
Coupling transformers	5000VA, 50 Hz
Nonlinear load	3 - phase uncontrolled bridge rectifier
Capacitors of AC side LPFs	C = 2.85mF
Reference voltage	$V_{dc(Ref.)}$ = 800 V
DC link reactor of CSC circuit	L_{dc} = 8000mH, R_{dc} = 0.01 Ω
Controller gains (PI) for DC link system	$K_{P(dc)}$ = 0.26 $K_{i(dc)}$ = 0.15
Controller gains (PI) for AC system	$K_{P(q)}$ = 0.5 $K_{i(q)}$ = 0.6
Switching frequency of CSC circuit	f_s = 20 kHz

The simulation run results under various operating conditions are presented below:

Case 1:

4.1. Model simulation results without operating the series APF

For observing the voltage and current waveforms at the PCC in the absence of series APF, the circuit breaker 1 is made closed so as to bypass the operation of the CSC based APF. Figure 8 (a) shows the load voltage waveforms which is monitored at the bus where the nonlinear load is connected.

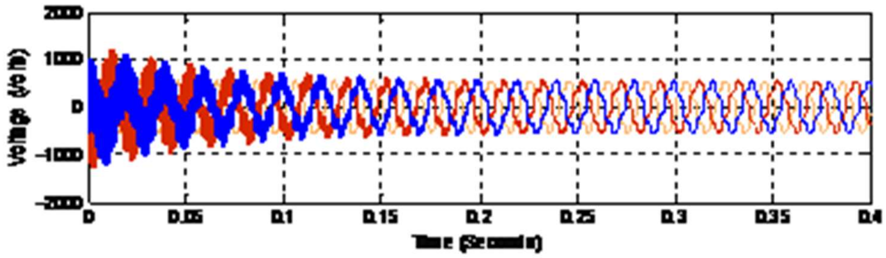

Figure 8 (a). Voltage waveform without series APF operation

Under this condition, the load voltage waveform is found to be highly distorted from zero to 0.15 seconds and from 0.15 seconds onward too, the voltage waveform is not sinusoidal due to the flow huge current harmonics from the nonlinear load to the distribution bus. With the help of a fast Fourier transform (FFT) analysis tools of the Matlab/Simulink platform, the total harmonic distortion (THD) value has been examined in this situation.

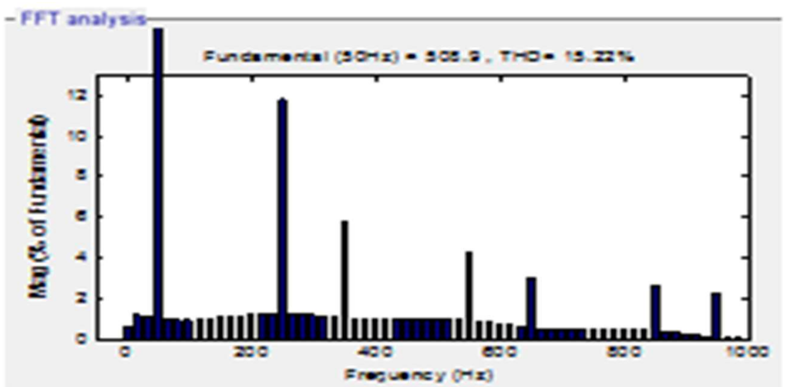

Figure 8 (b). Load voltage THD without series APF operation

As shown in Figure 8 (b), the load voltage THD value has been found to be very high i.e. 15.22 % which is far beyond the range specified by the international convention on harmonics adopted as "Recommended practices and requirements for harmonic control in electrical power systems" (IEEE standard 519:1992, 1993) [21].

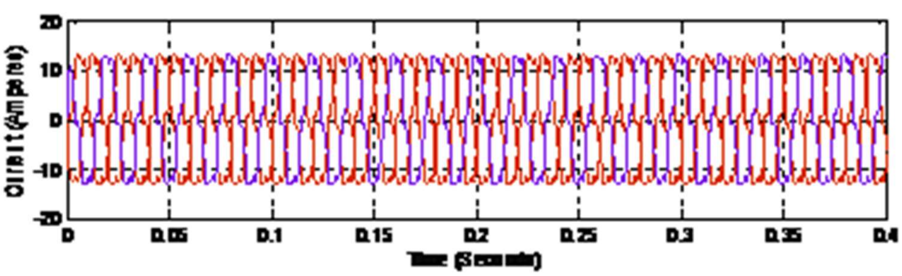

Figure 9 (a). Load current waveform without series APF operation

Fig. 9 (a) depicts the load current under this operating condition. It is observed to be containing lots of harmonics and its THD value is 15.05 % as shown in Figure 9 (b).

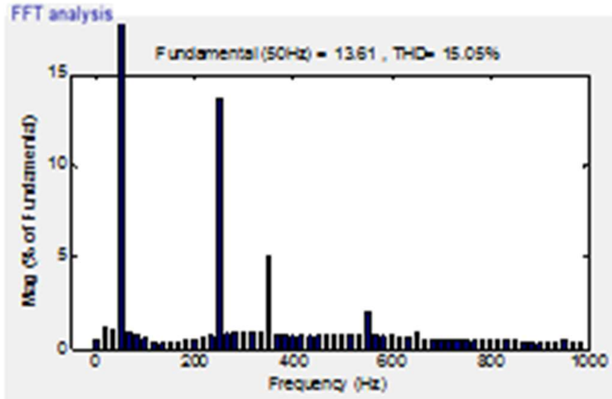

Figure 9 (b). Load current THD without series APF operation

Case 2:

4.2. Model simulation results with the operation of series APF

By closing the circuit breaker 1 of the Simulink model developed, the performance of the series APF has been investigated. Figure 10 (a) illustrates the voltage waveform observed. Under this operating condition, the voltage magnitude at the distribution bus where the nonlinear load has been connected is found to be 415 V i.e. 586 V (peak to peak) and sinusoidal.

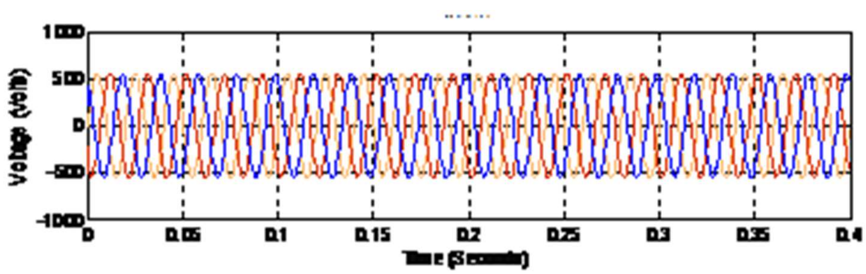

Figure 10 (a). Voltage waveform with series APF operation

Figure 10 (b) depicts the voltage THD value obtained from the FFT analysis under this condition. It is observed as 2.29 %. This THD value is fairly within the limits specified by the IEEE standard given in Table 10.2 [20].

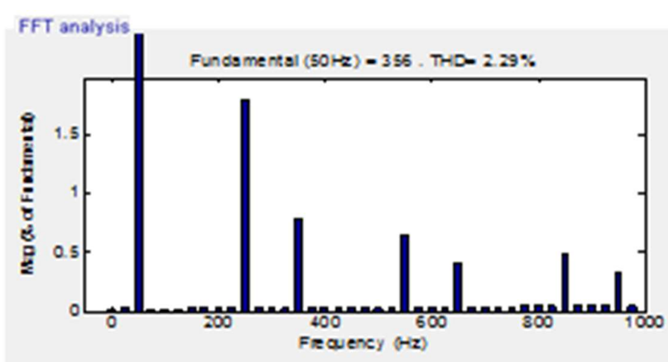

Figure 10 (b). Load voltage THD with series APF operation

Figure 11 (a) gives the load current waveform under the same operating condition.

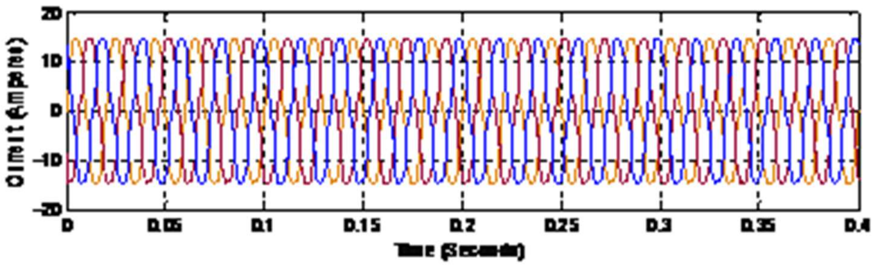

Figure 11 (a). Load current waveform with series APF operation

It is observed that the harmonics content has been reduced significantly in comparison with that of the load current waveform without operating the series APF shown in Fig. 9 (a). The THD value of this current is found to be 2.31 % as shown in Figure 11 (b).

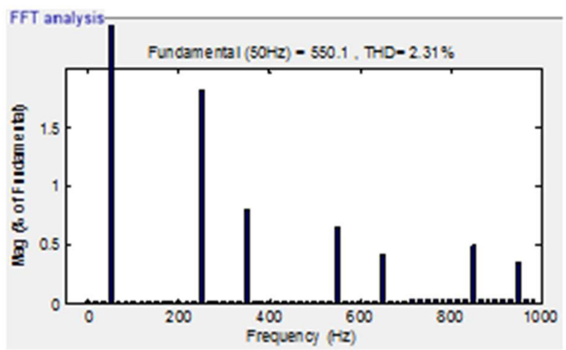

Figure 11 (b). Load current THD with series APF operation

From this simulation result, it is learnt that the proposed model is capable of mitigating the voltage as well as current waveform distortions caused by the nonlinear loads connected to the power distribution system.

5. Conclusion

In this paper, it has been attempted to explore the possibility of using CSC topology in the design and implementation of series APF for mitigating voltage as well as current waveform distortions caused by the nonlinear loads interfaced with a secondary power distribution system. It also discusses the major challenges encountered and their remedial measures with the CSC based approach. The results of simulation studies carried out on the proposed model reveal that CSC based series APF is capable of solving the PQ problems and thus provides improved power quality to the electric power consumers whose loads are sensitive to waveform distortions.

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