Journal of New Materials for Electrochemical Systems
Vol.27, No.2, June 2024, pp. 99-106
Journal homepage: http://iieta.org/journals/jnmes

Modelling of Multifunctional Voltage Source Converter for Unbalanced Solar PV Sources during Non-linear Loads

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https://doi.org/10.14447/jnmes.v27i2.a03

Received: November 4, 2023
Accepted: March 30, 2024

Keywords:
Multifunctional VSC, Harmonic Currents, Non-linear Loads, Unbalanced Sources, PI controller

ABSTRACT

This work aims to design, model and analyse an adaptive control method for voltage source converters (VSCs) under unbalanced PV sources and non-linear load operations. Both utility grids and stand-alone grid systems can use the proposed system. The VSC will inject Solar Photovoltaic(SPV) Power into the grid, to compensate fundamental component and harmonic reactive power, adjust the power factor, and balance the system's three-phase load when there is an imbalanced load. Shunt active power filters (APFs) have proven to be effective in filtering harmonic currents and correcting reactive power for linear/nonlinear loads. This research proposed a unique method for estimating the reference compensation currents of a three-phase shunt active power filter (APF) in a steady state under distorted and unbalanced source voltages (PV Sources). The suggested method is compared with three prior evaluated shunt APF reference compensating techniques. Even when the source voltages are significantly distorted and unbalanced due to variation in temperature and irradiation, the proposed system is compensating reactive power and harmonic/neutral currents of the load more effecetively. Furthermore, the suggested technique results in a simplified design of the shunt APF controller with three phase voltage source converter.

1. INTRODUCTION

Globally, the production of clean energy is a major problem. Non-conventional energy sources including solar, wind, fuel cells, and geothermal have shown to be viable answers in alleviating environmental concerns as a result of the depletion of fossil fuels. Among these, there has been a noticeable surge in solar photovoltaic (PV) systems [1]. These systems are linked to the distribution system by power electronics converters, and at the point of common coupling (PCC), intermittency causes variations in the voltage profile [2]. The effect of intermittency is countered by a current controller that operates in a positive sequence reference frame (PSRF) [3]. Nevertheless, PSRF has two significant drawbacks: In the event of voltage sag and swell, it first fails to maintain the intended voltage at PCC [4]. Secondly, it can only inject a balanced current into the system, which may result in problems with power quality when the network is unbalanced [5]. Different proposals have offered both voltage raise and unbalancing control approaches [6, 7]. Among these, two distinct methods are employed for voltage control: (i) actual power curtailment and (ii) reactive power compensation. Proposition [8] in the actual power curtailment approach assumes a maximum PV capacity of 15% of the peak load, whereas [9] permits PV capacities greater than 15% without going above the upper voltage limit. Both, however, advocate fixing the real power curtailment limitations, which is impractical given the possibility of shifting system operating conditions. Reactive power compensation is the second strategy, wherein a controller should provide the system with reactive power based on tight standards and connection codes in addition to active power via maximum power point tracking (MPPT) [10, 11].

Depending on the converter's power rating, the exchange should be kept within a triangle or rectangular reactive power capability curve, per standard [12]. Maintaining a 0.95 lead or lag power factor, the static grid support technology provides limited reactive power with decreased voltage [13]. In [14], the capability curve is extended for the effective use of the inverters' reactive power potential, moving from a rectangular to a circular characteristic. By providing double the reactive current (in pu) of the decreased voltage (in pu), the dynamic grid support approach regulates the voltage [15]. By anticipating system factors, the adaptive droop control approach enhances voltage regulation and transient responsiveness [16]. To create a reactive current reference, each of these methods calculates the minimal phase voltage difference between two instances at PCC. Consequently, during a malfunction, the produced current may raise the voltage of both the defective and healthy phases. Furthermore, the filter capacitor's size grows as PV capacity rises [17]. The reactive power produced by the filter capacitor under imbalanced conditions is most likely not taken into account in the literature currently in publication. The extra reactive power results in an inaccuracy while calculating the reactive power set point, which modifies the grid voltage profile. Moreover, in order to reduce the double fundamental frequency oscillation in both real and reactive power supplied into the network under imbalanced situations, a number of sequence controllers working in double synchronous reference frame are represented in [5, 18]. A reactive power exchange technique that injects balanced electricity into the grid during unbalanced conditions is presented in [19]. Numerous methods for adaptive control have been created, including adaptive shunt filtering control [22], model reference adaptive system update [21], and adaptive observer-based control [20]. However, these controllers only inject positive and negative sequence currents; they do not take into account the zero sequence components, which cause a zero sequence voltage in machines that are linked to a delta and a zero sequence current in machines that are connected to stars [23]. Therefore, in addition to the positive and negative sequence current controllers in the PV inverter's current control scheme, a zero sequence current controller is also needed.

This study proposes a sequence current controller with reactive power compensation to regulate the voltage of an imbalanced distribution network coupled to photovoltaic cells. The positive, negative, and zero sequence components of voltages and currents are separately and independently controlled to their corresponding reference commands by the proposed zero sequence controller and the enhanced positive and negative sequence controller using a combination of feedforward and feedback action. A method for calculating the dq components of voltage and current in zero sequence is suggested. In order to produce a reactive power reference, the suggested reactive power compensation approach takes into account both the reactive power provided by the filter capacitor and the positive sequence voltage at PCC. The suggested method addresses the problems of voltage decrease and increase, respectively, in both leading and lagging power factor scenarios. Positive sequence current reference is produced using a reactive power compensator and a DC-link voltage regulator. To create references for negative and zero sequence currents, a PCC voltage regulator is employed. To keep the voltage at the PCC balanced regardless of the unbalanced state, the voltage references of the negative and zero sequence PCC voltage controller are set to zero. With the use of a real-time simulator, the technique is evaluated for a variety of scenarios, such as imbalanced failures, shutting off loads, and VAR operating while cloud cover [24] for the IEEE 13 bus distribution network [25] with a PV system. A comparison study using current methods demonstrates the potency of the suggested control approach.

2. MODELLING OF ACTIVE POWER FILTER

Since the late 1970s, there has been considerable interest in the use of shunt active power filters (APF) to reduce harmonic currents and adjust reactive power for linear/nonlinear loads. The schematic architecture of a three-phase, four-wire shunt APF is shown in Fig. 1, where the APF monitors source voltages and load currents to calculate the appropriate compensating currents. For estimating the reference compensation currents needed to inject into the network at the connected point of the nonlinear load, Akagi presented the instantaneous reactive power theory (i.e., p-q theory). Many publications dealing with active power filter compensation solutions have been inspired by the notion since then. The ability of a shunt APF to be generated without active energy source components, such as batteries, or in other forms in its compensating mechanism is one of its distinctive characteristics. In other words, a perfect APF doesn't use any of the average actual power that the source supplies. For both reactive power and harmonic/neutral current compensation of the load, this function necessitates an efficient reference compensation technique. Most current APF reference compensation solutions are decided with or without reference-frame modifications. To establish the APF reference compensation currents in the three-phase, three-wire system, for instance, the theory suggested and necessitates the translation of both source voltages and load currents from the a-b-c reference frame to the alpha-beta reference frame. The premise is to handle the zero-sequence power compensation with a more complex controller architecture for implementations of the APF in a three-phase, four-wire system. For harmonic and reactive power adjustment in the reference frame, the authors suggested the generalized instantaneous reactive power theory. The suggested method has the advantages of not requiring reference-frame translation and allowing for a more straightforward APF controller design.

The load currents at the fundamental frequency will be obtained using a synchronous reference frame approach using the desired source currents. After that, the load currents are subtracted from the basic components to provide the APF reference compensation currents. When the source voltages are amplitude-imbalanced, a technique was proposed in the reference frame to preserve perfect three-phase source currents. The methods described above should provide enough harmonic and reactive power adjustment for nonlinear loads at ideal source voltages. On the other hand, if the source voltages are unbalanced and distorted, the generated APF reference compensation currents are inconsistent, and the intended balanced/ sinusoidal source currents cannot be maintained. Standard methods for estimating the APF reference compensation currents include maintaining sinusoidal source currents that provide the load with average actual power. It has been demonstrated that the APF can outperform other techniques when using the sinusoidal source current strategy. This study proposes a unique method to identify the shunt APF reference compensation currents, even when the source voltages and load currents are unbalanced and distorted, in order to accomplish full compensation of both reactive power and harmonic/neutral currents of the load. The suggested method, which is a reference-frame-based method classified as a sinusoidal source current strategy, is comparable to others that have been previously given. The three options suggested in the first described are briefly reviewed in this paper. The utility of the suggested strategy and the examined approaches is then compared using Matlab/Simulink simulations.

Active filters need an external power source and are implemented using a combination of passive and active (amplifying) components. Active filter designs commonly employ operational amplifiers. These can produce resonance without inductors and have high Q. The bandwidth of the amplifiers, however, restricts their top frequency limit. The typical method of building multiple-element filters is a ladder network. These may be viewed as a development of the L, T, and designs of the filters. When enhancing certain filter properties, such as stop-band rejection or the slope of the pass-band to stop-band transition, more components are required.

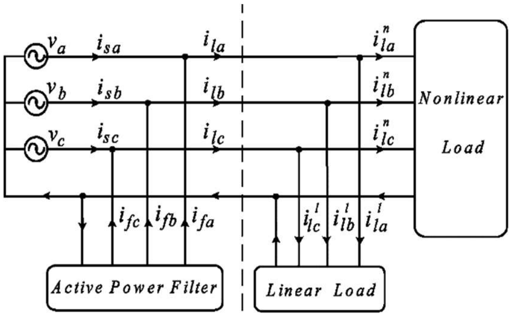

Figure 1. Line diagram of 3-phase shunt active filter

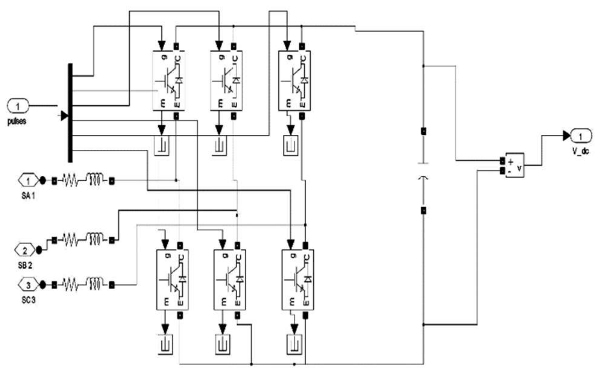

Figure 2. A three phase voltage source converter with IGBTs

To examine the APF system's performance, a three-phase system supplying an inverter load has been chosen. The non-linear properties of power electronics loads cause the THDs of source current and terminal voltage to be significantly lower than those required by IEEE-519. In order to create a clean sinusoidal current wave in phase with the supply voltage, the APF system, in theory, injects a current equal in amplitude but out of phase with the harmonic current. Figure 1 depicts a simplified power system's single-line diagram with the APF system turned on. The voltage source inverter (VSI), which is IGBT-based, is the brain of the APF system presented in Figure 2. A DC capacitor delivers the power for the VSI. The capacitor voltage must be at least 150% of the maximum line-line supply voltage for the APF to function properly. The PWM VSI is represented as a current amplifier with unity gain since it is supposed to be instantaneous and infinitely fast to follow the compensatory currents.

Figure 3 depicts the closed loop control circuit diagram of pulse generation scheme for three pahse VSI from three phase reference currents. The source currents must be balanced, undistorted, and in phase with the positive-sequence source voltages in order for the active power filter's proposed compensation technique to work. The shunt APF control has four main objectives: 1) achieving unity source power factor at positive-sequence fundamental frequency; 2) behavior of the average actual power used or provided by the APF;

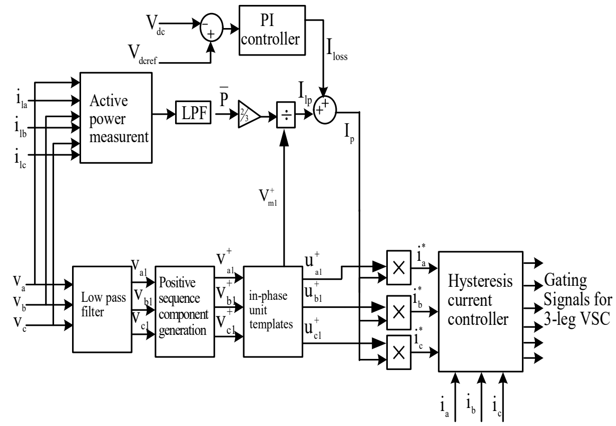

Figure 3. Control circuit for pulse generation to the IGBTs of APF

3) compensating for harmonic current; and 4) compensating for neutral current. In order to fully compensate for the nonlinear load, the active power filter must supply harmonic/neutral currents and reactive power. To accomplish these objectives, the intended three-phase source currents must be in phase with the positive-sequence fundamental source voltage components.

3. OPERATION OF THREE PHASE VOLTAGE SOURCE CONVERTER

Consider each terminal as a voltage source that is connected to the AC transmission network via a three-phase reactor to understand the foundations of VSC transmission functioning. As schematically depicted in Figure 4, the two terminals are linked by a DC connection.

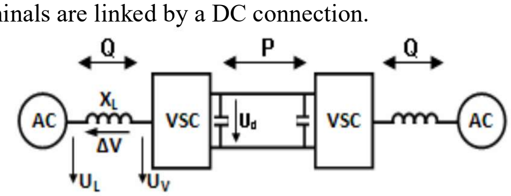

Figure 4. Line diagram of voltage source converter

The VSC converter is connected to an AC network by a transformer's inductance, as shown in Figure 5 with phasor diagram. The DC voltage as shown in Eq(1) is proportional to the fundamental voltage on the valve side of the converter transformer, or UV(1).

$$UV(1) = kuUd \tag{1}$$

By adding more commutations each cycle, or using a pulse with modulation (PWM), one may regulate the amount ku. The formulae for the active and reactive power are as follows when the apparent power definition is used and the transformer resistance is disregarded: If the power flows from the AC network to the converter, the active and reactive power will be characterized as positive. If the converter output voltage is out of phase with the AC voltage, the phase displacement angle will be positive.

Reactive power is regulated by the modulation index (m) control in Figure 6, whereas the control of δ controls the active power or the DC voltage. The dq can be used to indicate both the real and fictitious power of the inverter at any given time on the valve side.

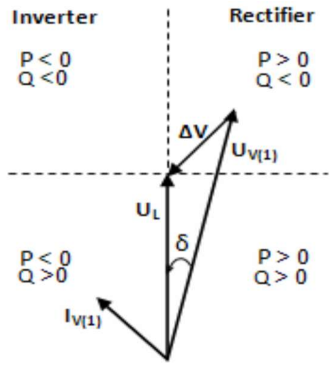

Figure 5. Power flow vector diagram of VSC specifying modes of operation

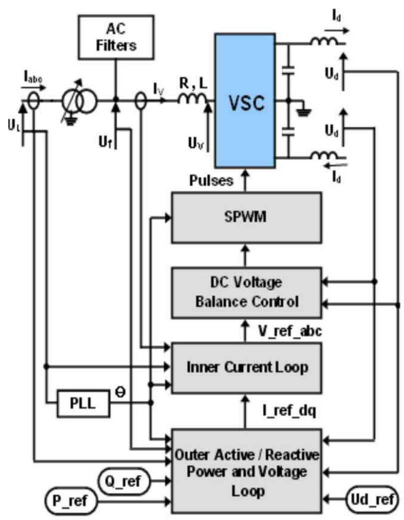

Figure 6. Closed loop control operation of VSC

4. TWO-AXIS REPRESENTATION OF THREE-PHASE CURRENTS

The active filter's control method is focused on producing reference source currents. Synchronous frame reference theory (SRF) is used to produce these reference source currents. As feedback signals, the load currents (i_{la}, i_l, i_l), PCC voltages (v_a, v_b, v_c), and dc-link voltage (V_{dc}) are monitored. The load currents in a-b-c coordinates are converted into d-q coordinates using Park's transformation. The load currents d-q components are determined as follows:

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \tag{2}$$

Cosθ and sinθ are calculated using a three-phase PLL in that case. These d-axis and q-axis currents may be divided into oscillatory and average components, as in,

$$i_{ld} = \overline{i}_{ld} + \tilde{i}_{ld} \tag{3}$$

$$i_{lq} = \overline{i}_{lq} + \tilde{i}_{lq} \tag{4}$$

The inverse Parks transformation is used to convert the reference source currents from their original d-q to a-b-c coordinates.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta \\ \cos\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{2\pi}{3}\right) \\ \cos\left(\theta+\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \end{bmatrix}\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \tag{5}$$

4.1 PWM Current Controller

Comparisons are made between the felt source currents (i_a, i_b, and i_c) and the reference source currents (i_a*, i_b*, and i_c*). The PWM current controller produces the ON/OFF switching patterns for the gate drive signals to the IGBTs. The most recent mistakes are calculated as,

$$i_{aerr} = i^*_{\ a} - i_a;\ \ i_{berr} = i^*_{\ b} - i_b;\ i_{cerr} = i^*_{\ c} - i_c \tag{6}$$

For the purpose of switching the IGBTs of the VSC of the active filter, these current error signals are sent to a carrierless PWM current controller seen in Figure 7.

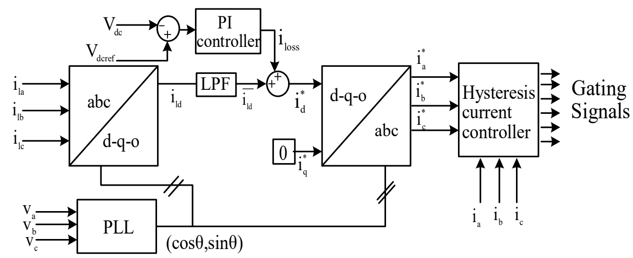

Figure 7. Pulse generation scheme using hysteresis controller

4.2 PWM for Power Balance Theory

The active filter's control method is focused on producing reference source currents. Power balance theory (PBT) is used to create the reference source currents. As feedback signals, the load currents (i_{la}, i_l, i_l), PCC voltages (v_a, v_b, v_c), and dc-link voltage (V_{dc}) are monitored.

Three phase voltages are measured and amplified at the generator terminals (v_a, v_b, and v_c) to determine their amplitude as,

$$V_t = \sqrt{\frac{2}{3}\left(v^2_{\ a} + v^2_{\ b} + v^2_{\ c}\right)} \tag{7}$$

DC bus voltage error V_{dcer} at the nth sample moment is written as,

$$V_{dcer(n)} = V_{dcref(n)} - V_{dc(n)} \tag{8}$$

The detected DC link voltage of the CC-VSC is $V_{dc(n)}$, and V_{dcref} is the reference DC voltage. The PI controller's output is described as, "This keeps the DC bus voltage of the CC-VSC at the nth sampling instant."

Comparing the detected source currents (i_a, i_b, and i_c) with the reference source currents (i_a*, i_b, and i_c). The PWM current controller generates the patterns of ON/OFF switching for the gate drive signals to the IGBTs. These are the current mistakes calculated as,

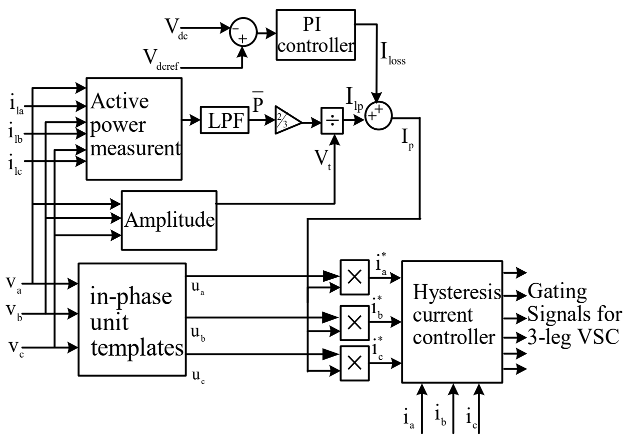

Figure 8. Pulse generation through carrier less PWM

$$i_{aerr} = i^*_a - i_a;\; i_{berr} = i^*_b - i_b;\; i_{cerr} = i^*_c - i_c \qquad (9)$$

To switch the IGBT of the VSC of the active filter, these current error signals are sent to a carrierless PWM current controller.

5. RESULTS & DISCUSSIONS

Usually, due to variable irradiance and variable temperature, the power output of the PV sources always not constant. In this particular analysis, three PV sources of different ratings are considered for generating three phase AC source. The output voltages of the three PV sources are plotted in the figure 9 seen below. From the figure 9 is it seen that the PV1 produce the voltage of 48V, PV2 produces 96V and PV3 produces 192V respectively.

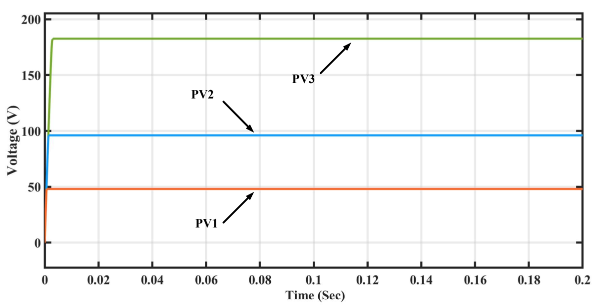

Figure 9. Variable output voltage of the PV sources

The voltage source converter is implemented in this research for multipurpose use, which is termed as multifunctional converter. i.e., The voltage source converter (VSC) is modelled as shunt active power filter (APF) to compensate the unbalanced source voltages, unbalanced load currents, reactive power compensation under non-linear load operations etc. The performance waveforms of the power system operation with active power filter-based control are depicted below to analyze the system behaviour with unbalanced and non-linear loads under steady-state operation.

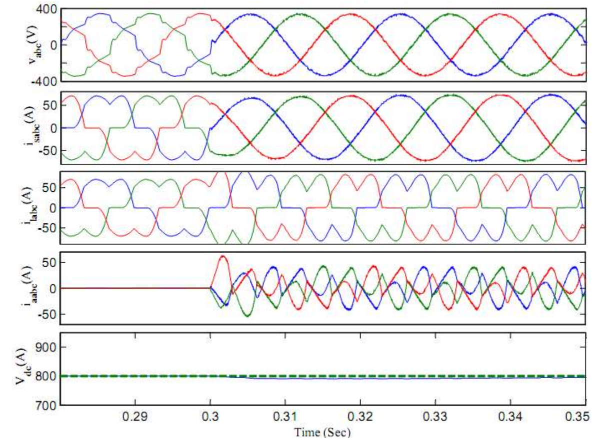

Figure 10. Line voltage and line current waveforms with non-linear loads.

The three phase line currents were presented in figure 10 for non-linear loads. Here a fault is created at 0.3s and observed the disturbance in the line voltages and line currents at the same time without using active power filter. From the above figure it is observed that, during the fault period the line current i_{abc} in Phase-C is zero and there is some distortion in Phase-A and Phase-B, Also dc link voltage also becomes zero when the non-linear loads are fed.

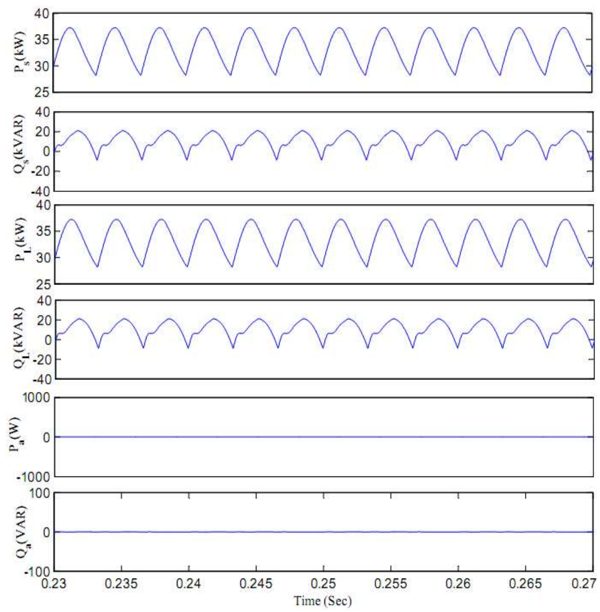

Figure 11. Power output from the supply without compensation

The active and reactive power supplied by the sources, active and reactive power output of the loads have seen in figure 11, and also presented the Power delivered by APF without compensation. Here without compensation the APF deliver zero power into the line which are represented with P_a for active power delivered by the APF and Q_a for reactive power delivered by the APF in the figure 11.

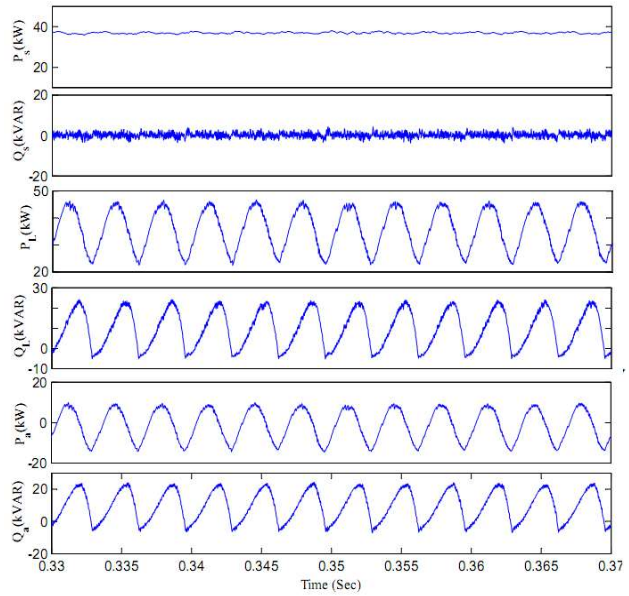

Figure 12. Power output from the supply with compensation

The active and reactive power supplied by the sources and the active and reactive power output of the loads are seen in Figure 12 and also present the Power delivered by APF with compensation.

The three-phase line currents were presented in Figure 13 for linear loads. Here, a fault is created at 0.3s and the disturbance in the line voltages and line currents at the same time without using an active power filter.

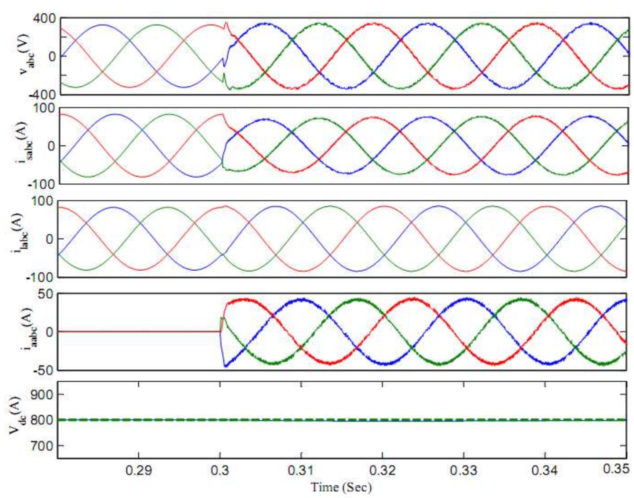

Figure 13. Line voltage and line current waveforms with linear loads.

The three phase source currents and load currents were presented in figure 14 with unbalanced source voltages without reactive power compensation.

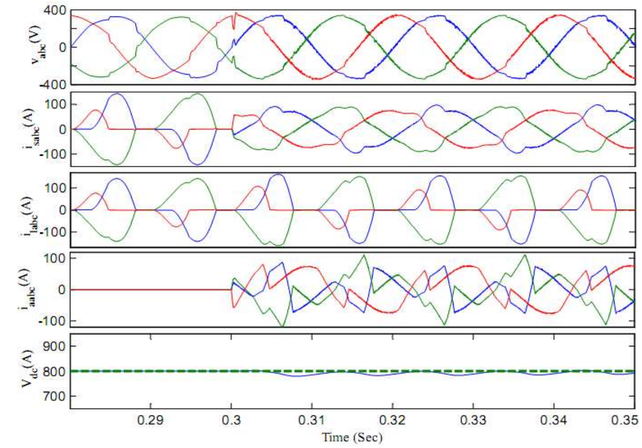

Figure 14. Source current and load current waveforms with unbalanced source voltages without compensation

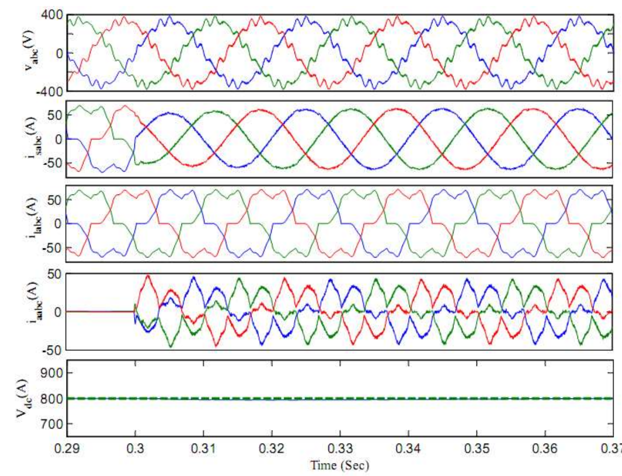

Figure 15. Source current and load current waveforms with unbalanced source voltages with reactive power compensation by APF

The three phase source currents and load currents were presented in figure 15 with unbalanced source voltages with reactive power compensation

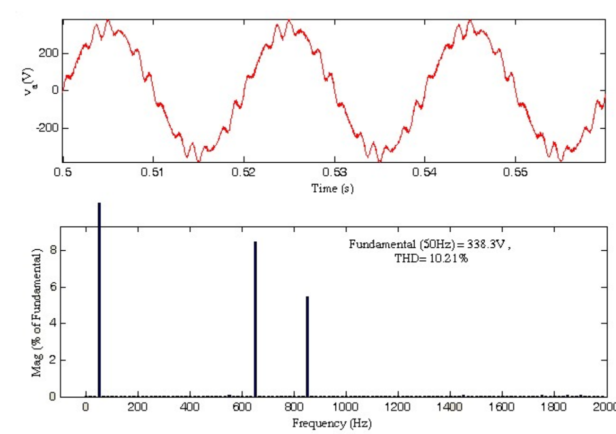

Figure 16. THD of load voltage during unbalanced source voltages

The THD of output voltage is measured for the unbalnced source voltages and is obtained as 10.21% for afundamental volateg of 338.3V as seen in Figure 16.

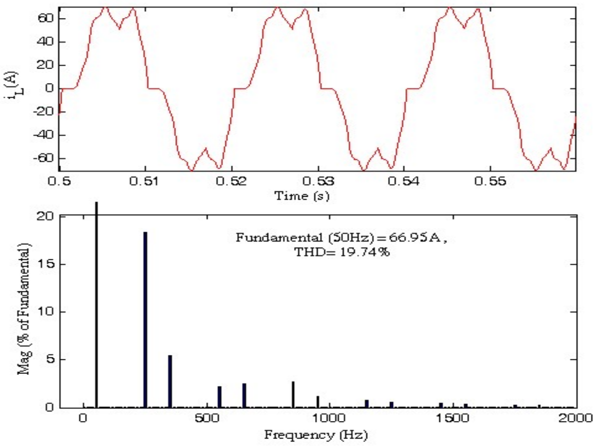

Figure 17. THD of load current for nonlinear loads without compensation

The THD of load current is measured during the non-linear loads without reactive power compensation and is obtained as 19.74% for a fundamental current of 66.95A, as seen in Figure 17.

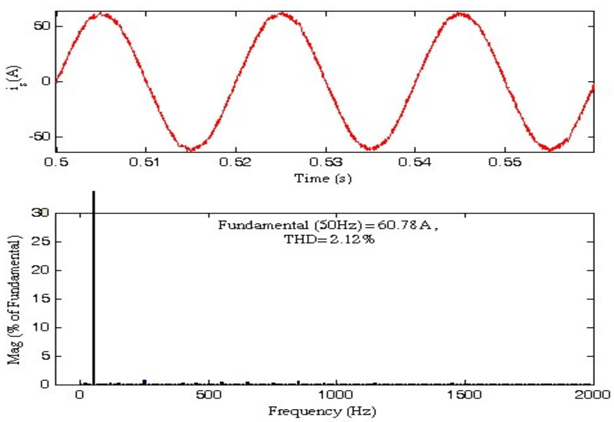

Figure 18. THD of the load current with reactive power compensation using APF

The THD of load current is measured during the non-linear loads with reactive power compensation and is obtained as 2.12% for a –fundamental current of 60.78A, as seen in Figure 18.

6. CONCLUSIONS

The sole technique whereby any distortion of the source current must be sinusoidal and the loads might be linear, non-linear, balanced, or unbalanced. This enables us to support the recommended manner of approach. The load current's harmonic and reactive components are demonstrated to be removed by the AF, leaving behind sinusoidal and source currents with a power factor of unity. It has been demonstrated that the source current always remains lower than the load current, even under temporary circumstances. The AF boosts system efficiency since the source does not have to handle the reactive and harmonic power needed by the load. This study offered a novel approach to computing the reference compensation currents of a shunt active power filter (APF)'s three phases in a steady state when the source voltage was distorted and imbalanced. The proposed approach was compared to three previously studied shunt APF reference compensation procedures. A common technique to determine the APF reference compensation currents is to maintain sinusoidal source currents while providing an average of actual power to the load. It has been shown that when employing the sinusoidal source current strategy, the APF outperforms alternative methods.

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