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Design of an Asymmetrical Three-phase Inverter for Load Balancing and Power Factor Correction Based on Power Analysis

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Abstract – This paper presents a novel theoretical method based on power analysis to obtain voltage reference values for an inverter-based compensator. This type of compensator, which is installed in parallel with the load, is usually referred to as the active filter. The proposed method is tailored to design the compensator in such a way that it can simultaneously balance the asymmetric load, as well as correct the power factor of the supply side. For clarity, a static compensator is first considered and a recursive algorithm is utilized to calculate the reactance values. The algorithm is then extended to calculate voltage reference values when the compensator is inverter based. It is evident that the compensator would be asymmetric since the load is unbalanced. The salient feature associated with the proposed method is that the circuit representation of system load is not required and that the load is recognized just by its active and reactive consumptions. Hence, the type and connection of load do not matter. The validity and performance of the new approach are analyzed via a numerical example, and the obtained results are thoroughly discussed.

Keywords: Asymmetrical inverter, Load balancing, Power analysis, Power factor correction

1. Introduction

Unbalanced loads and poor power factors are two crucial challenges associated with electric power distribution systems. Load unbalancing and reactive power flow, which is the direct consequence of poor power factor, increase the losses of the distribution system and cause a variety of power quality problems. Accordingly, the reactive power compensation has become an issue with a great deal of importance. Static var compensators have been broadly investigated and deployed to balance the three-phase loads and to compensate the reactive power they absorb [1]-[3]. Primary examples of these compensators are designed based on thyristor switched capacitors (TSCs) or thyristor controlled reactors (TCRs) [3]. However, recently, switching power converters are becoming more popular as reactive power compensators. The most significant merit associated with this type of compensator is that no large energy storage elements are required. Other advantages have been discussed in [4].

One of the power electronic devices being utilized for load balancing and reactive power compensation is the voltage source inverter (VSI) [5]-[11]. In this type of inverter, some electrical variables are controlled in order to achieve the best desirable operating status. Miscellaneous methods are available for obtaining control parameters and signals in static var compensators and VSIs [12], [13].

In majority of relevant literature, the formulation associated with active and reactive powers has been deduced while assuming the load as three impedances with delta or star connection. Accordingly, the proposed formulas are mainly valid for passive loads and are not able to represent active loads [14], [15]. Active loads, such as induction motors, cannot be modeled by pure impedances since they comprise voltage or current sources operating along with impedances. On the other hand, representing three-phase loads only by associated active and reactive power consumptions, instead of representation by impedances, results in a general method for both active and passive loads where the load type and connection do not matter. This method is the basis for the algorithm presented in [1] to calculate the reactance associated with each phase of a delta-connected compensator. Less electrical signal measurement is needed in this method compared to those required by methods proposed earlier; hence, the scheme is also computationally simple as it does not require complicated calculations.

Although SVCs are very effective system controllers used to provide reactive power compensation and load balancing, their limited bandwidth, higher passive element count that increase size and losses, and slower response are some of the limitations associated with them. As a good alternative, VSI-based compensator provides excellent capabilities to overcome the abovementioned drawbacks [16]. In addition, operating SVCs in both capacitive and inductive modes is expensive or even impossible in static compensators, but very simple in VSIs. Thus, VSI-based compensator exhibits a very good operation in this regard. With

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respect to these advantages, in this paper, the algorithm formerly proposed by [1] is improved to obtain reference voltages of a three-phase VSI. The proposed algorithm first calculates the value of reactances for a static compensator. Based on the results obtained, the voltage reference values of the inverter-based compensator are computed. The controllers employed for the inverter are simple proportional-integral (PI) controllers, which are among the responsible for maintaining the DC capacitor voltage as constant and also set the inverter output voltage at the reference value. Either or both power factor correction and load balancing goals can be achieved through the designed compensator. The validity of the algorithm is investigated through an example, and simulation results are discussed in details.

2. Static Var Compensator Design

The relation between active and reactive powers is fundamental of the work presented in this paper. Fig. 1 shows a three-wire three-phase load supplied by a source with balanced voltages. Assuming phase R as the angle reference, voltage phasors would be

$$V_R = V\angle 0 \ , \ V_S = V\angle -120 \ , \ V_T = V\angle 120 \, .$$

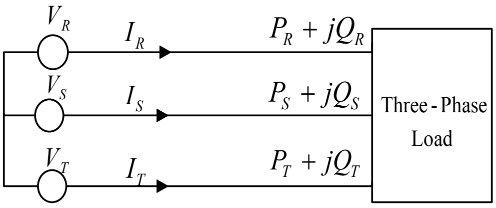

Fig. 1. Three-phase load

In Fig. 1, assuming I_R, I_S, and I_T as the phase currents of the system, we have the following equation:

$$\begin{aligned} & I_R^* + I_S^* + I_T^* = 0 \\ & \frac{P_R + jQ_R}{V\angle 0} + \frac{P_S + jQ_S}{V\angle -120} + \frac{P_T + jQ_T}{V\angle 120} = 0 \end{aligned} \qquad (1)$$

In (1), it can be deduced that having identical values for the reactive powers leads to the equality of active powers [1]. That is,

$$If \quad Q_R = Q_S = Q_T \ \Rightarrow \ P_R = P_S = P_T \, . \qquad (2)$$

The system will be balanced if the condition expressed by (2) holds. Balancing the reactive powers would simultaneously balance the active powers. Accordingly, in the proposed methodology, only reactive powers and voltages values are measured as feedback signals to control the compensator.

Now, assume that a three-phase static var compensator is connected in parallel with the load, as illustrated in Fig. 2, to balance phase currents. The reactive powers delivered to the initial load in three phases are measured using three VAr meters. Detailed explanations about the measurement techniques are available in [17]. In this figure, the total reactive power delivered to the load is given by (3).

$$Q_L = Q_R^L + Q_S^L + Q_T^L \qquad (3)$$

The compensator is composed from three reactances with delta configuration. The reactive powers for the three phases of the compensator are designated by Q_{RS}^C , Q_{ST}^C , and Q_{TR}^C ; in the sequel, the compensator line reactive powers, as shown by Q_R^C, Q_S^C , and Q_T^C in Fig. 2, can be obtained as follows [1]:

$$\begin{aligned} Q_R^C &= \frac{Q_{RS}^C + Q_{TR}^C}{2} \\ Q_S^C &= \frac{Q_{ST}^C + Q_{RS}^C}{2} \\ Q_T^C &= \frac{Q_{TR}^C + Q_{ST}^C}{2} \end{aligned} \qquad (4)$$

The reactive powers associated with the compensator should be adjusted so that the whole system is seen balanced from the supplier standpoint.

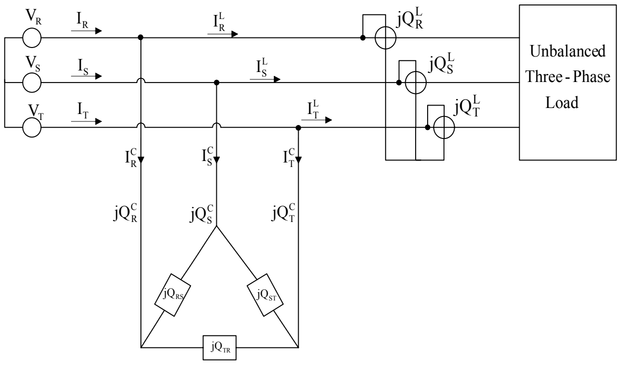

Fig. 2. Static var compensator in parallel with the unbalanced load

In the following with respect to Fig. 2, we define Q_{eq} as the total reactive power delivered to the load-compensator group from the supply-side view. Q_{eq} would be equal to Q_L in the case where the aim is only to make the whole system balanced and without any power factor correction; however, Q_{eq} should be zero when the purpose is balancing the system along with making the power factor unity. Theoretical calculations agree that in order to make the system balanced, the reactive power associated with each phase of the load-compensator group should be $\frac{Q_{eq}}{3}$ [1].

From the supply-side perspective, the reactive power of each phase is the sum of the load and compensator reactive powers corresponding to that phase. Hence, we would have the following equation:

$$
\begin{aligned}
\frac{Q_{eq}}{3} &= Q_R^L + \frac{Q_{RS}^C + Q_{TR}^C}{2}\\
\frac{Q_{eq}}{3} &= Q_S^L + \frac{Q_{ST}^C + Q_{RS}^C}{2}\\
\frac{Q_{eq}}{3} &= Q_T^L + \frac{Q_{TR}^C + Q_{ST}^C}{2}
\end{aligned}
\tag{5}
$$

In (5), Q_{eq} is known according to the load balancing and power factor correction purposes. Q_R^L, Q_S^L, and Q_T^L are also known as the load characteristics. Therefore, three unknown values, i.e., Q_{RS}^C, Q_{ST}^C, and Q_{TR}^C, could be determined using the three equations available. A simple calculation results in the following:

$$
\begin{aligned}
Q_{RS}^C &= \frac{Q_{eq}}{3} + Q_T^L - Q_R^L - Q_S^L\\
Q_{ST}^C &= \frac{Q_{eq}}{3} + Q_R^L - Q_S^L - Q_T^L\\
Q_{TR}^C &= \frac{Q_{eq}}{3} + Q_S^L - Q_R^L - Q_T^L
\end{aligned}
\tag{6}
$$

Reactive powers obtained by (6) are used to calculate reactance values of the compensator as follows:

$$
X_{RS}^C = \frac{V_{RS}^2}{Q_{RS}^C},\quad X_{ST}^C = \frac{V_{ST}^2}{Q_{ST}^C},\quad X_{TR}^C = \frac{V_{TR}^2}{Q_{TR}^C}
\tag{7}
$$

Where V_{RS}, V_{ST}, and V_{TR} are the phase-to-phase voltages and are measured from the network.

3. Calculation of Compensator Reactances with Recursive Algorithm

Two main set of equations, i.e., (6) and (7), are used in this algorithm to obtain the reactance values of the static var compensator. First, initial value of reactances are calculated by (7) and based on the initial reactive powers obtained by (6). The reactive powers of the supply side will change after connecting the compensator with the initial reactances. The load and compensator are then assumed to be a new load that is still unbalanced. For this new defined load, Q_R^L, Q_S^L, Q_T^L will have new values. This recursive state occurs because of the existence of line impedances that were cause by this process, the three-phase currents and voltages converge together after several iterations. In the next iterations, the reactance values are modified using (7) and based on the new reactive powers obtained by (6). The process will proceed until the settlement of the calculations, namely the reactive power of all phases of the load-compensator group, are equal to $Q_{eq}/3$. Fig. 3 depicts the flowchart of the computation:.

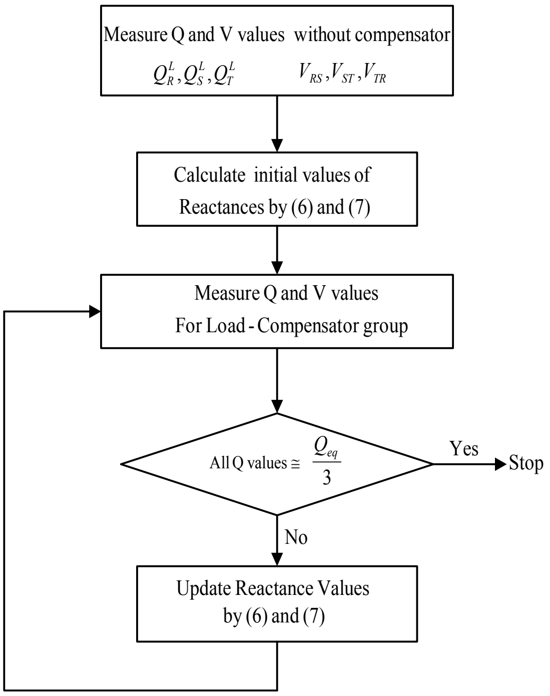

Fig. 3. Recursive method to calculate compensator reactances

4. Three-phase Inverter-based Compensator

Fig. 4 shows the three-phase inverter connected in parallel with the load. In this figure, C_f and L_f denote the components associated with a filter.

Each leg of the three-phase inverter could be equalized by either a capacitor or an inductor, as illustrated by Fig. 5. In this figure, E stands for the output voltage of the leg in question, X is the reactance of the transformer located between the inverter and the network, and V is the phase-to-phase voltage of the network.

By determining the compensator reactances X^C, the currents through these reactances can be defined, as shown by (8).

$$
I = \frac{V}{X^C}
\tag{8}
$$

If the circuit acts as a capacitor, the magnitude of voltage E is calculated by (9). This value, which is greater than V in magnitude, is referred to as the reference output voltage for the considered leg of the three-phase inverter.

$$
|E| = |V| + |XI|
\tag{9}
$$

In the case where the leg of the inverter operates in the inductive mode, a similar calculation leads to the following expression:

$$
|E| = |V| - |XI|
\tag{10}
$$

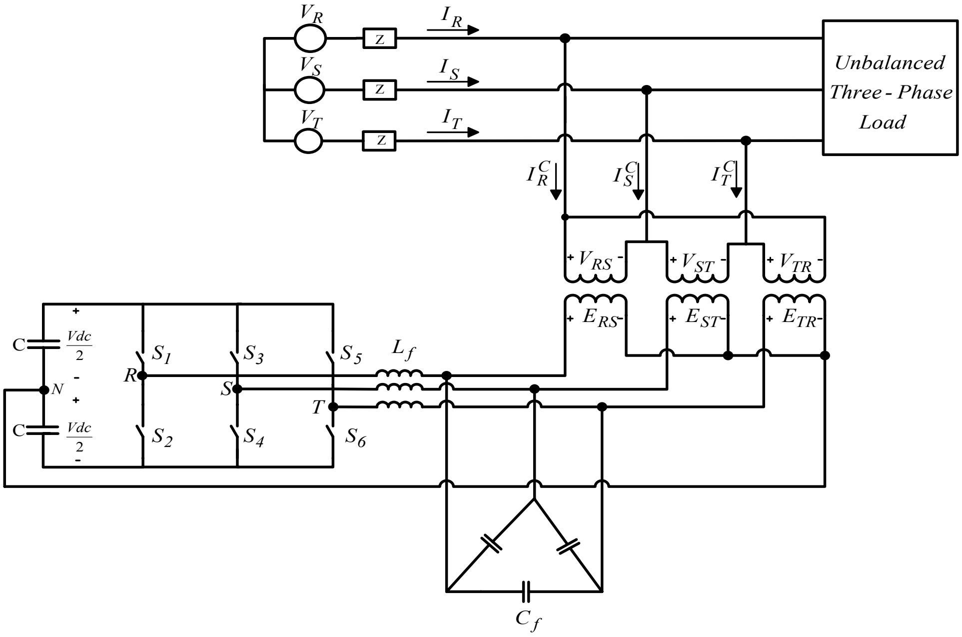

Fig. 4. Three-phase inverter for compensation

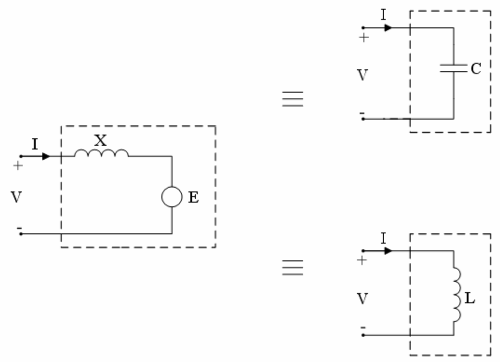

Fig. 5. Equal circuit for each leg of the three-phase inverter

Based on the sign of the compensator reactances X^C (identified by a polarity detector), each leg in the three-phase inverter will be in the capacitive or inductive mode. When X^C is negative, the corresponding leg will be in the capacitive mode and (9) is used to calculate the reference output voltage for that leg. On the other hand, when X^C is positive, the corresponding leg is in the inductive mode and (10) is used to calculate the reference output voltage for that leg [18]. The procedure to calculate three reference output voltages associated with the legs of the inverter is added to the algorithm presented by Fig. 3. The flowchart of the extended algorithm is demonstrated in Fig. 6.

4.1. Switching Strategy

The switching strategy in the inverter is assumed to be based on the well-known pulse width modulation (PWM) method. Fig. 7 shows a single phase-leg of the three-phase bridge converter. Fig. 8 (upper) compares the two types of control signals. These signals are the three sine waves with

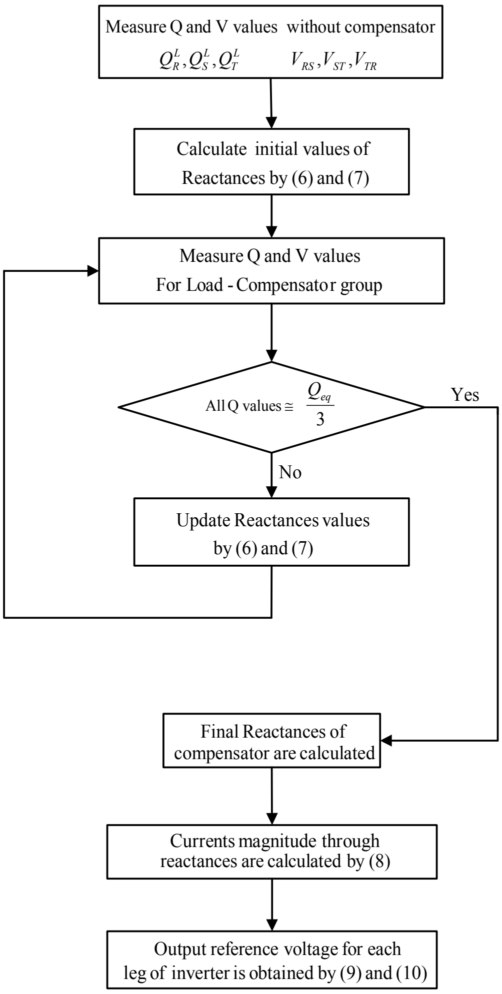

Fig. 6. The extended algorithm to calculate the reference voltages of the inverter-based compensator

the main frequency representing three phase-to-phase voltages $V_{control}$(RS), $V_{control}$(ST), and $V_{control}$(TR), as well as the sawtooth wave signal whose frequency is multiple of the main frequency. Turn-on and turn-off pulses for switching devices correspond to the crossing points of the sawtooth wave with the sine wave of that phase. The negative slope of the sawtooth wave crossing the sine wave of $V_{control}$(RS) results in a turn-on pulse for switch 1 and concurrently a turn-off pulse for switch 2. In contrast, the positive slope of the sawtooth wave crossing the sine wave of $V_{control}$(RS) results in a turn-off pulse for switch 1 and concurrently a turn-on pulse for switch 2. The resulting voltage of the AC terminal *R*, with respect to the hypothetical midpoint *N* of the DC capacitor, is shown in Fig. 8 (lower). The figure reveals that pulses are wider in the middle of each half sine wave compared to those corresponding to both ends of the half-cycle [18].

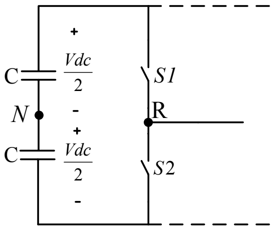

Fig. 7. A single phase-leg of the inverter

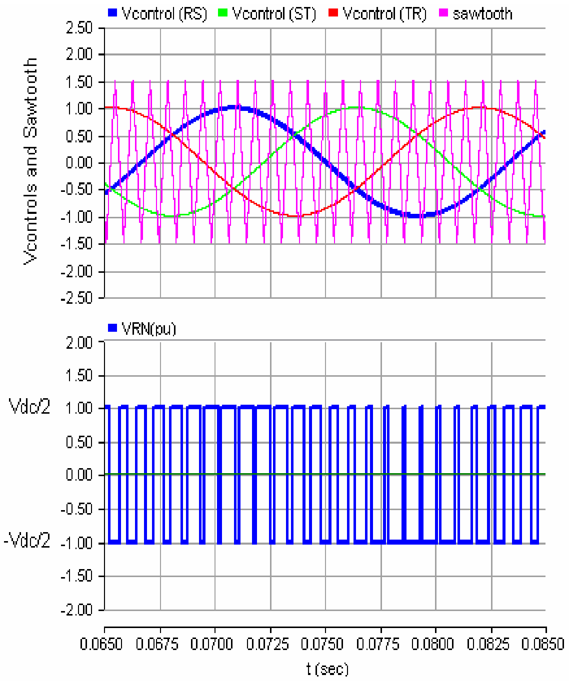

Fig. 8. PWM waveforms: (upper) three-phase control signals and the sawtooth wave; and (lower) the voltage of the AC terminal *RN*

With a fixed sawtooth wave, an increase in the sine wave magnitude would increase the conduction time of switch 1 and decrease the conduction time of switch 2 for the positive half-cycle, and vice versa for the negative half-cycle. That is, the fundamental component of the AC voltage V_{RN} and consequently the output AC voltage would increase with an increase in the magnitude of the control sine wave and decrease with a decrease in the magnitude of the control sine wave. While the peak of the control sine wave is less than that of the sawtooth wave, the output AC voltage varies linearly with respect to the variation in the control sine wave [18]. Similar discussions could be raised for phases *S* and *T*.

5. Control System for Three-phase Inverter-based Compensator

Two substantial tasks are described for the three-phase inverter: power factor correction and load balancing. Accordingly, two different controllers associated with these responsibilities are to be allocated to the inverter: controlling the DC bus voltage and controlling the inverter output voltage in each leg. Inverter output voltage control can be achieved either by a direct control, in which both the angular position and the magnitude of the output voltage are controlled, or by an indirect control, in which only the angular position of the output voltage is controlled and the magnitude remains proportional to the DC terminal voltage [18]. In this paper, the control structure used for the inverter model is based on direct control.

Fig. 9 shows the control system. The DC capacitor voltage control is achieved by a small phase displacement "e" beyond the required 0 degree between the inverter voltage and the network voltage. The error signal obtained by comparing V_{dc} with $V_{dc(ref)}$ is passed through a PI controller, which generates the required phase angle displacement or "e".

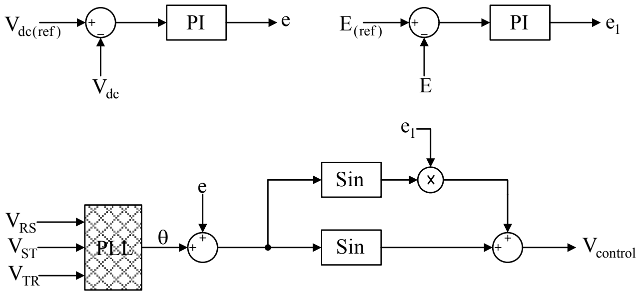

Fig. 9. Control system for three-phase inverter

The second controller is responsible for setting the inverter output voltage of each leg equal to the reference voltage obtained by the algorithm. This can be done by letting the difference between the reference voltage and the output voltage of each leg pass through a PI controller. The PI controller output "e_1" is used to adjust the magnitude of the control sine wave. The output voltage of the inverter leg would consequently be set to the reference value.

In order to provide a better understanding of the operation of the control system, a mathematical equation is obtained for $V_{control}$ based on the generated control signals "e" and "e_1".

$$V_{control} = (1+e_1)\cdot Sin(\theta + e) \tag{11}$$

The phase angle "e" is utilized to produce the required phase displacement between the inverter output voltage and that of the network; hence, the DC capacitor voltage is kept constant. Moreover, for each leg, the signal "e_1" is used to adjust the amplitude modulation index in order to set the inverter output voltage at the reference value obtained via the algorithm.

6. Simulation Results

The system employed for the simulation consists of a three-phase 1,224 V source with impedance of 0.01 + j0.25 Ω, an active load between *R* and *S* phases, and two passive loads between *S* and *T* as well as between *T* and *R* phases. The load is completely unbalanced and is not a pure passive load. Details about the load are given in Table 1.

Table 1. Load data

Parameters	Values
RS load	$E = 495\angle -30\ ,\quad X = j11.3$
ST load	300 + j37 Ω
TR load	150 + j37 Ω

Fig. 10 shows the source currents of the three phases. The magnitudes of the currents are not the same, thus the system is unbalanced.

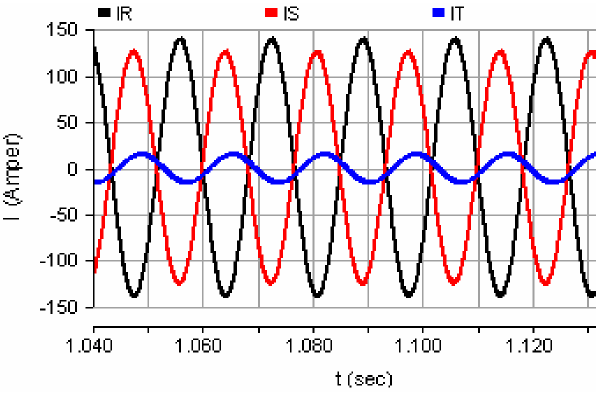

Fig. 10. Source currents before compensation

6.1. Load Balancing Without Power Factor Correction

In this section, the purpose of the compensation is to make the load balanced without any change in the power factor value; accordingly, the Q_{eq} is set at Q_L. It is assumed that a three-phase inverter is connected in parallel with the load, as earlier depicted in Fig. 4. The reference voltages associated with the inverter are obtained by employing the proposed algorithm. The reference voltages for the inverter are determined as follows:

$$E_{RS} = 1751\ V, E_{ST} = 1107.3\ V, E_{TR} = 773.1\ V$$

The generated inverter voltages are shown in Fig. 11. The magnitudes of the generated voltages are unequal with each other. Hence, the inverter is an asymmetric one.

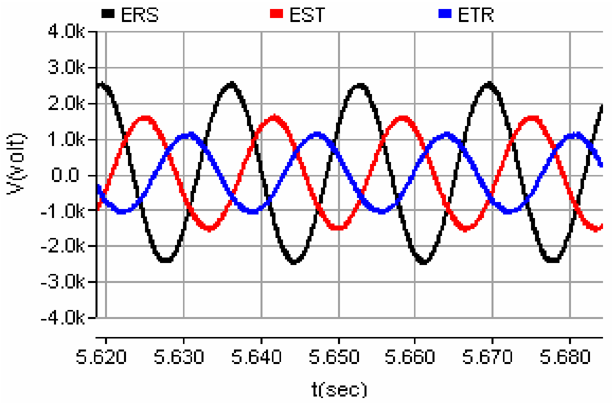

Fig. 11. Inverter voltages

After connecting the inverter-based converter to the system, the source currents, depicted in Fig. 12, are of the same magnitudes and are entirely balanced. For the simulations, the stopping criterion for the proposed algorithm is defined such that the difference of the reactive power in each phase with the value of $Qeq/3$ should be less than 0.5 kVAr. This is the reason why the trivial differences in the source currents are observed. However, the algorithm will proceed to reach to a precise balance condition if the number of iterations is increased. The source reactive powers, which are the summation of the load-compensator group reactive powers, are shown in Fig. 13. The active powers of the supply side are illustrated in Fig. 14. In these figures, it can be observed that before connecting the inverter to the system, i.e., t < 1 sec, the three-phase reactive powers as well as the active powers of the supply side are unequal with each other. On the other hand, when the inverter is connected to the system at t = 1 sec, the three-phase reactive powers become equal with each other in the value of $Q_L/3$;furthermore, the phase active powers become identical and equal to one-third of the total three-phase active power. Accordingly, the load would be considered completely balanced from the source view. The transient behaviors, shown in Figs. 13 and 14, occur when the inverter is connected to the system due to the charging of the inverter DC bus capacitor and its controller operation. These transient conditions disappear rapidly and will not raise serious concerns.

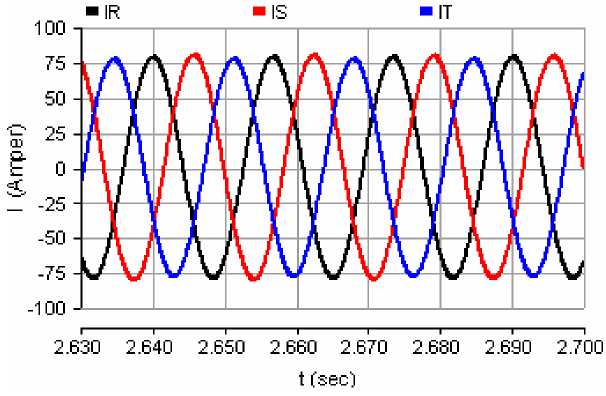

Fig. 12. Source currents by connecting the compensator

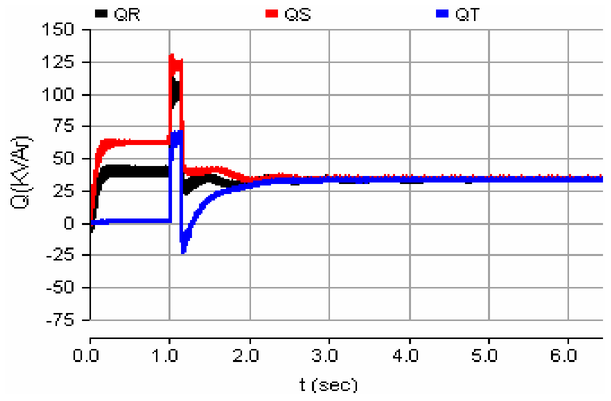

Fig. 13. Source reactive powers by connecting the compensator

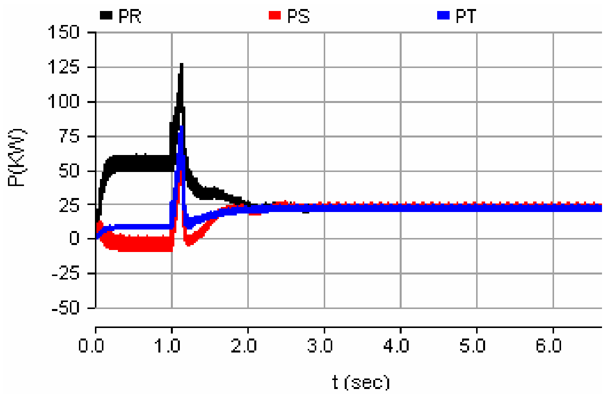

Fig. 14. Source active powers by connecting the compensator

6.2. Load Balancing and Power Factor Correction

In order to make the system balanced and to improve the power factor to unity, the three-phase inverter is connected in parallel with the load, as earlier depicted in Fig. 4. Based on the purpose of compensation, Q_{eq} is set to zero. The reference voltages associated with the inverter are obtained by using the proposed algorithm. The reference voltages for the inverter are determined as follows:

$$E_{RS} = 2053.5\ V, E_{ST} = 1392\ V, E_{TR} = 1059.2\ V$$

The inverter-generated voltages for achieving the desired compensation are shown in Fig. 15.

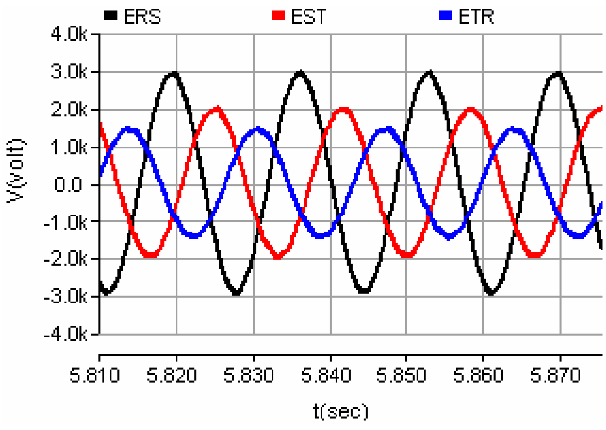

Fig. 15. Inverter voltages

By connecting the inverter-based converter to the system, the source currents, depicted in Fig. 16, are of the same magnitudes and are balanced. The source reactive powers, which are the summation of the load-compensator group reactive powers, are shown in Fig. 17. The active powers of the supply side are illustrated in Fig. 18, while the power factor of the system is depicted in Fig. 19. In these figures, it can be observed that before connecting the inverter to the system, i.e., t < 1 sec, the reactive powers of the supply side are not set to zero; hence, the power factor is not unity and the three-phase active powers of the supply side are unequal. On the other hand, when the inverter is connected to the system at t = 1 sec, the three-phase reactive powers approach zero, consequently enabling the power factor to become unity. The phase active powers become identical and equal to one-third of the total three-phase active power. Accordingly, the load would be considered completely balanced with unity power factor from the source view.

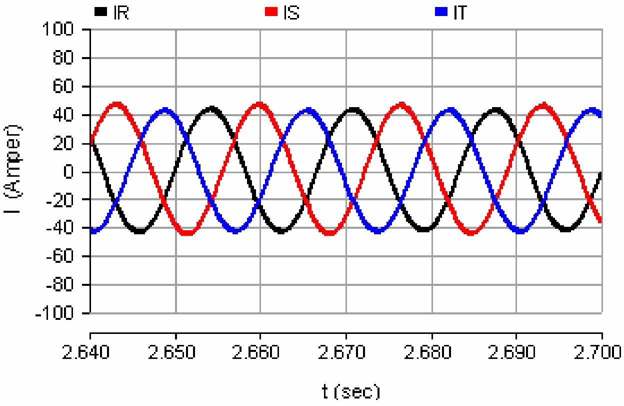

Fig. 16. Source currents by connecting the compensator

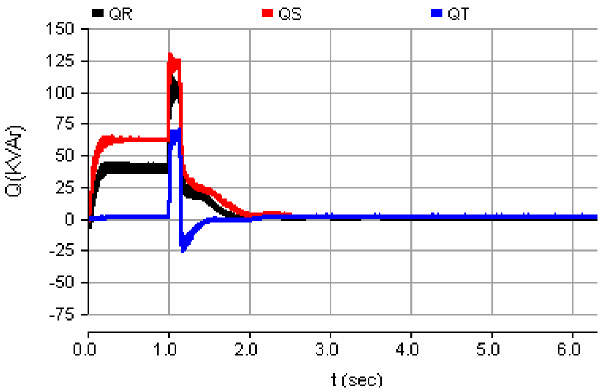

Fig. 17. Source reactive powers by connecting the compensator

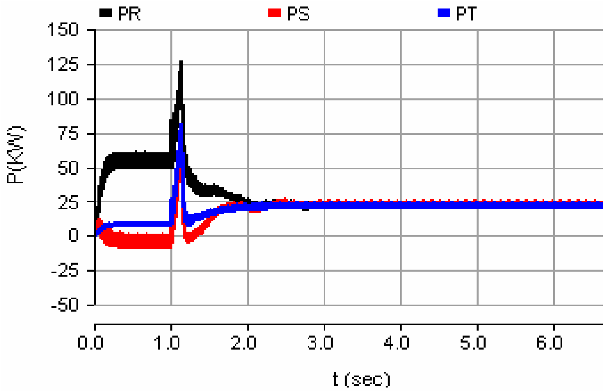

Fig. 18. Source active powers by connecting the compensator

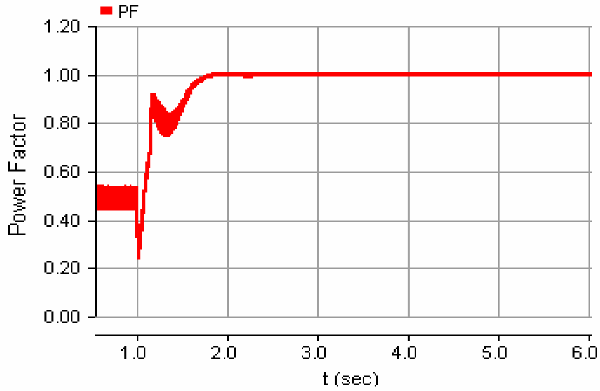

Fig. 19. Power factor of the system

7. Conclusion

This paper developed a new algorithm to calculate reference voltages of a three-phase voltage source inverter for balancing unbalanced loads and power factor correction. The algorithm was based only on power values to describe the load, and this feature made the method valid for the case of active loads as well. Two different case studies were considered. In the first attempt, the purpose of compensation was only to make the load balanced without any change in the power factor value. In the second case, load balancing and power factor correction were taken as the targets of compensation. The simulation results demonstrate the validity and effective performance of the proposed method in both cases. The scheme is also computationally simple as it does not require complicated calculations.

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