Control of power converter used for electric vehicle DC charging station with the capability of balancing distribution currents and reactive power compensation

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ABSTRACT

The global interest in electric cars aims to achieve sustainability in the transportation sector and reduce dependence on conventional cars that mainly depend on fossil fuels, the main source of emissions polluting the environment. However, the electric cars required electric fast chargers to charge the batteries with high currents in order to make the electric cars competitive with conventional cars that required a short time for filling fuel. Single-phase electric chargers make the distribution feeders with unbalanced currents as the single-phase loads and single-phase PV inverters. In the case of the unbalanced operation, one of the three phases may reach its maximum limit before other phases which leads to disconnect the transformer and thereby inefficient and unreliable system operation. This paper presents a control scheme for a three-phase, four-leg power converter that can be used as a fast charger for electric cars. Moreover, it can be used for balancing grid currents and for reactive power compensation. This will avoid frequent interruptions of distribution transformers due to unbalanced operation and reactive power loads. The distribution feeder considered to evaluate the control scheme consists of single-phase loads and inverters in addition to the proposed converter. The converter controls the charging power effectively and balancing the feeder currents. Moreover, during off charging time which is a possible manner for the charging station when the EV battery is fully charged the converter is effectively used for unbalanced mitigation and reactive power compensation. The simulated results show the effectiveness of the proposed control scheme.

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1. INTRODUCTION

Conventional transportation systems depend on fossil fuels which are considered the most important sources of environmental pollution that leads to global warming and other environmental issues. Therefore, the world is moving towards replacing conventional cars with electric vehicles (EVs) which are considered environmentally friendly [1]-[3]. For example, the European Commission recommended that the total number of petrol and diesel cars needs to be decreased to fifty percent by 2030. Also, it is recommended that by 2050 the conventional cars should be completely phased out [4]. Electric energy is used to power the motors of EVs instead of using fuels like gasoline and diesel in conventional vehicles. Therefore, EVs battery must be periodically recharged by an external electrical power source, it is often the electrical grid. Different studies have been conducted on using renewable energy for charging EVs, a study has indicated that 14 - 50% of public transportation in a medium-sized city in Europe can be provided with electrical power generated from solar photovoltaic systems [5], [6]. The main advantage of using renewable energy is to mitigate the power demand increasing of EVs chargers from the main grid.

The expected widespread of EV single-phase chargers' adaption will add a significant unbalanced load among the main grid phases mainly at distribution networks [7]. The unbalanced operation of the distribution network will result in overloading the distribution transformer, which also leads to a serious increase in losses and voltage unbalance [8], [9]. Furthermore, the unbalanced network can host less renewable energy power generation like PV systems because the critical voltage and current limits is reached in one phase before other phases [10], [11]. The unbalanced voltages of the three phases occurred due to passing the unbalanced currents into the electrical feeders. Different solutions are presented to balance the currents in three-phase distribution feeders. An approach of manually switching the phases by the distribution system operator (DSO) is presented in [12]. This mitigates unbalanced by distributing the load equally in the three phases. This solution is very costly especially at the distribution level, where the power in each phase rapidly changes, which results in more switching actions [13], [14]. Alternatively, static transfer switches (STS) are used to switch the residential loads from one phase to another in order to balance three-phase loads as presented in [15]. However, this solution is costly because it requires the use of STS. Another approach is presented in [16], where a control scheme for a three-phase voltage source inverter with four-legs is used to deliver the negative sequence currents depending on the measurements of the negative sequence voltages. The case of single-phase inverters is different than residential loads, where disconnecting the PV inverters during energy production will lead to energy loss which makes lower revenue and longer payback periods [13].

The electric cars required electric fast chargers to charge the EV batteries with high currents to make the electric cars competitive with conventional cars that required a short time for filling fuel. However, consuming high electric currents in short periods will lead to an unbalanced voltage drop and overloading the distribution feeders and transformers. The charging curtailment can limit this drop and can lead to an extension of charging time which is unwanted by EVs users [17].

Motivated by the above issues, this paper presents a control scheme for a three-phase four-leg power converter used as an active rectifier that converts AC power to DC required for charging EVs. As well, the converter is used for balancing the unbalanced grid currents and for reactive power compensation during charging. In case of no need for charging the EVs, the converter is used for balancing the distribution currents and for reactive power compensation. The proposed scheme overcomes overloading conditions of the electrical feeders and distribution transformers due to uneven currents among its three-phase wires, and this improves the operation and the efficiency of power system components.

2. SYSTEM STRUCTURE

The DC charging is considered in this study because it is faster than AC charging [18]. In Figure 1, the electrical network consists of a single-phase PV inverter, single phase load, and distribution transformer. The proposed power converter is used as a front-end rectifier interfaced with the network through an LCL passive filter. It converts the AC power from 3 phase, 4 lines system to DC power which feeds the battery charger for charging the battery of EV. The DC/DC converter is used to control the charging current and charging voltage required for the battery during the charging process. For vehicle batteries, it is important to control the charging current and charging voltage to maintain the charging process within the battery manufacturers' recommendations. The control of the DC/DC converter is beyond the scope of this paperbecause this study is focusing on the control of the AC/DC converter.

3. POWER CONVERTER AND PROPOSED CONTROL STRATEGY

Two basic topologies of power converters are used for unbalanced compensation in the three-phase power system. The first, converter of three legs with a split DC-link capacitor, where the three phases are connected to the three legs and the neutral line is connected to the mid-point of a split capacitor. This topology is well organized. However, it produces distorted output voltages even with large DC-capacitors [19]. The second, converter with four-leg is shown in Figure 2. This converter is presented in several significant research papers where unbalanced compensation is required. The additional leg with two switches S7and S8 is connected to the neutral line and it is used to control the zero-sequence current [20], [21].

When the three-phase voltage source converter (VSC) supplying balanced active and reactive powers, the vector control scheme can be employed in high-performance, where the balanced currents are transformed in a synchronously rotating frame (abc-dq0) [22]. On the other hand, using the VSC for unbalanced compensation makes the converter output currents unbalanced depending on the unbalanced currents required to be compensated. Therefore, the output currents must be transformed into symmetrical components [23]. Symmetrical components are generally transformed into individual positive, negative, and zero sequence components in dq0. This is necessary to use an effectively simple proportional and integral (PI) controller [23], [24]. The extraction of positive, negative, and zero components are required to decompose the unbalanced measured currents. As shown in Figure 3, the alpha component for each phase is the same current measured value, while the beta component is obtained by using the time delay of the quarter, in case the frequency is 50 Hz, the time delay period amounts to 5 ms. After getting α-β components of each phase current the d-q transformation is obtained by (1) [24].

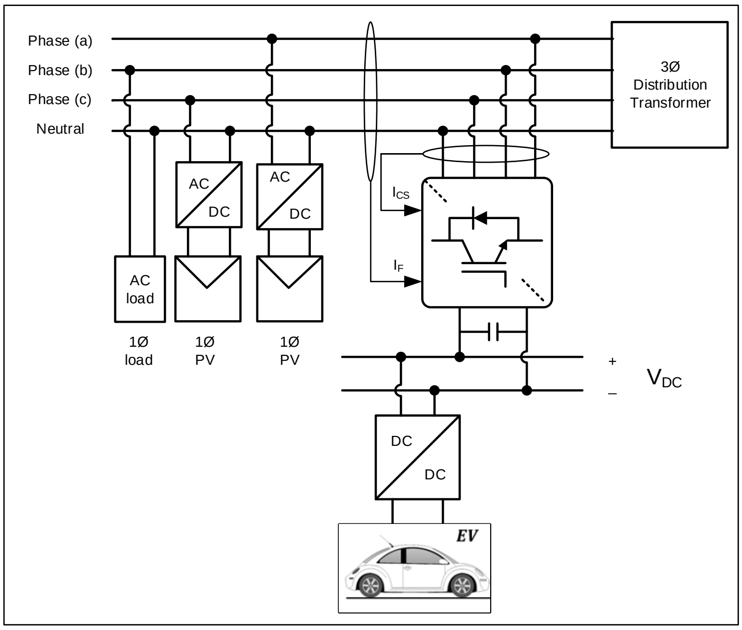

Figure 1. EV charging station system structure

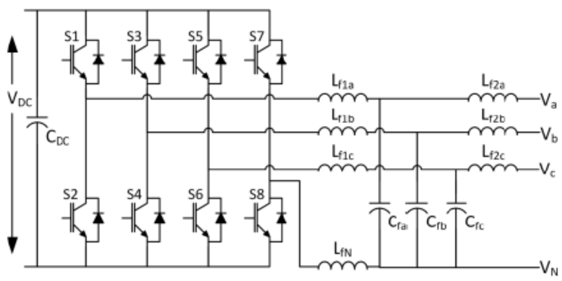

Figure 2. Four leg power converter with LCL filter

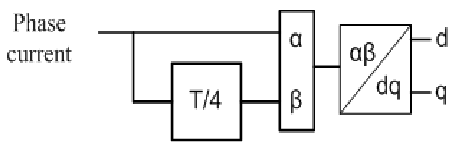

Figure 3. The delay of quarter period to get d-q for each phase

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} sin(\omega t) & -cos(\omega t) \\ cos(\omega t) & sin(\omega t) \end{bmatrix} \times \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{1}$$

The complex form of d-q frame for positive, negative, and zero sequences obtained by (2).

$$I_d + jI_q = \begin{bmatrix} 1 & j \end{bmatrix} \times \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{2}$$

$$\begin{bmatrix}(I_d+jI_q)_p\\(I_d+jI_q)_n\\(I_d+jI_q)_z\end{bmatrix}=\frac{1}{3}\times\begin{bmatrix}1 & a & a^2\\1 & a^2 & a\\1 & 1 & 1\end{bmatrix}\times\begin{bmatrix}(I_d+jI_q)_a\\(I_d+jI_q)_b\\(I_d+jI_q)_c\end{bmatrix} \quad (3)$$

where I is the unbalanced currents and a is the operator with the value presented in (4).

$$a = e^{j\times 2\times\pi/3} \quad (4)$$

After getting the d-q quantities of positive, negative and zero sequences of the inverter output currents (I_{CS}) and the feeder unbalanced currents (I_F) illustrated in Figure 1. The current control loop is used to make the desired negative and zero components of converter currents (I_{CS}) to be the same as the negative and zero components of the unbalanced feeder currents (I_F) as shown in Figure 4. The positive sequence d-q quantities are used to control the required active power to charge the battery and to control the reactive power which required for reactive power compensation as shown in Figure 5.

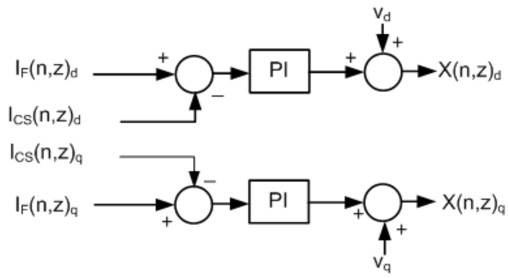

Figure 4. Control loop of negative and zero sequence

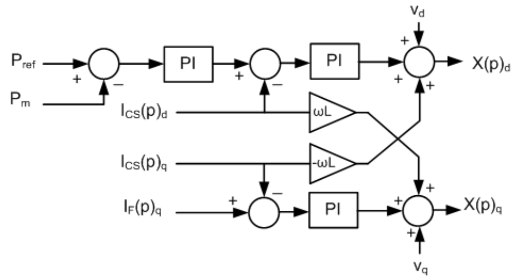

Figure 5. Control loop of positive sequence

After the control loops and getting the values of X_d and X_q of positive, negative, and zero sequences, these values are converted to α-β frame by using (5).

$$\begin{bmatrix}X_\alpha\\X_\beta\end{bmatrix}=\begin{bmatrix}sin(\omega t) & cos(\omega t)\\-cos(\omega t) & sin(\omega t)\end{bmatrix}\times\begin{bmatrix}X_d\\X_q\end{bmatrix} \quad (5)$$

Then, (6) is used to get the signals X_a, X_b, and X_c , these three signals are the inputs for the carrier pulse width modulation (CPWM) used for converting the three reference signals into the four required gating signals needed to switch the four-legs converter. CPWM is equivalent to a 3D-SVM according to [24], [25], but with an easier implementation, and therefore it is used in this study.

$$\begin{bmatrix}x_a\\x_b\\x_c\end{bmatrix}=\begin{bmatrix}1 & 0 & 1\\-\frac{1}{2} & \frac{\sqrt{3}}{2} & 1\\-\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1\end{bmatrix}\times\begin{bmatrix}x(p)_\alpha+x(n)_\alpha\\x(p)_\beta-x(n)_\beta\\x(z)_\alpha\end{bmatrix} \quad (6)$$

4. SIMULATION RESULTS

In order to test the proposed converter control scheme, the considered unbalanced transmission feeder consists of single-phase loads and single-phase PV inverters as shown in Figure 1. The simulations carried out for the proposed control strategy via the computer simulation software, MATLAB/Simulink, using the parameters listed in Table 1.

The active and reactive power of the PV inverters and loads in each phase are listed in Table 2. It can be observed in Table 2, the sum of active power generated from PV inverters amounts to 23 kW, and the sum of the loads active power amounts to 10 kW. The net or excess active power amounts to 13 kW generated from different PV inverters can be used to charge EV battery via prosed converter also it can be delivered to the grid in case no need for charging the EV.

Table 1: The parameters of the proposed converter and control loops

Item	Value
The grid voltage (3Ø)	400 V
Input filter inductor	8mH
output filter inductor	4mH
Filter capacitor	30μF
Current loop controller proportional term	50
Current loop controller integral term	800 s^{-1}
Outer loop power controller proportional term	0.02
Outer loop power controller integral term	15 s^{-1}

Table 2: Active power and reactive power of single phase inverters and loads

Item	Active power (kW)	Reactive power(kVar)
Phase a	PV (P=10), Load (P=3)	Load (Q=0)
Phase b	PV (P=8), Load (P=2)	Load (Q=4)
Phase c	PV (P=5), Load (P=5)	Load (Q=2)

The reference power P_{ref} shown in Figure 5, is the input for positive current control loop. This reference value is to control the active power required for charging the EV battery. In Figure 6, the simulation period is divided into two sub-periods, in the first period (t = 0 → 1s), the power required to charge the battery is set to be 20 kW with negative value indicated the power absorbed by the converter. In the second sub-period (t = 1s → 2s) the value of P_{ref} changed to be zero as in the cases, the battery of EV is fully charged or in the case the charging station is not used for charging the EV.

It can be seen in Figure 7, that, the inverter delivers unbalanced active power depending on the power of positive, negative, and zero sequence. It is worth noting that the total power for the three phases amounts to -20 kW and 0 in the first and second simulation periods respectively.

As previously explained, excess active power generated from PV inverters amounts to13 kW and the EV charging power in the first simulation sub-period amounts to -20 kW. Therefore, the required power from the grid amounts to 7 kW as shown in Figure 8. In the second simulation sub-period, the transformer power amounts to -13 kW feedback into the grid.

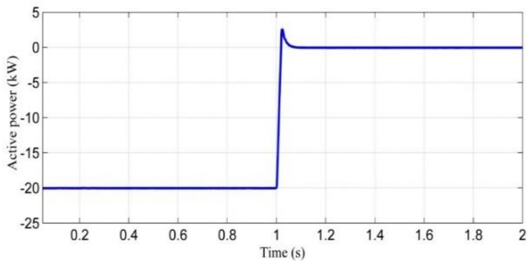

Figure 6. Converter total three phase active power (kW)

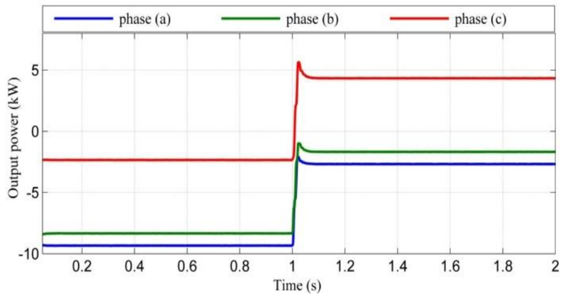

Figure 7. Converter output active power for each phase (kW)

As illustrated in Table 2, the reactive power of load in phase (b) and phase (c) amount to 4 and 2 kVar respectively while no reactive power is demanded in phase (a). The total reactive power in the three phases amounts to 6 kVar which is required to be compensated by the converter. It can be observed in Figure 9 that, the converter delivers reactive power of 4 kVar and 2 kVar for case (b) and case (c) respectively with total reactive power delivered from the converter amounts to 6 kVar. It is worth noting, each of the converter phases delivers an amount of reactive power depending on the reactive power demanded in each phase.

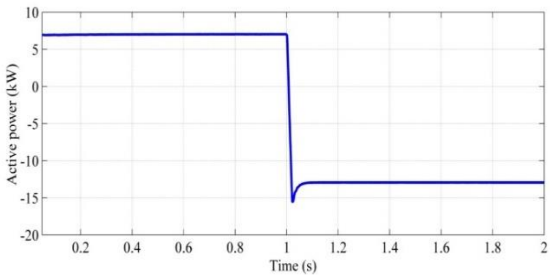

Figure 8. Grid three phase active power (kW)

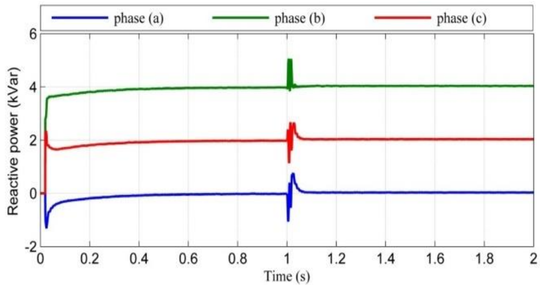

Figure 9. Converter output reactive power of each phase (kVar)

Figure 10 shows the total amount of reactive power delivered from the converter amounts to 6 kVar. This amount of reactive power remains constant in both simulation sub-periods. In Figure 11, as desired, the transformer reactive power amounts to zero, which approves that the converter compensates the required reactive power and makes the transformer working with unity power factor. This will enhance the reliability of the system by preventing frequent disconnections due to unbalanced and overload conditions.

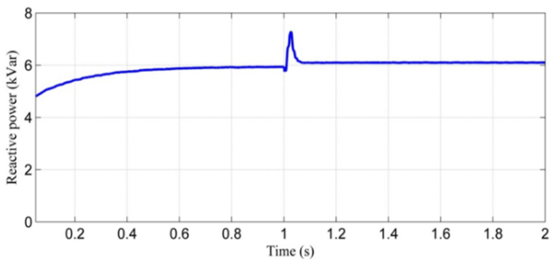

Figure 10. Converter total three phase reactive power (kVar)

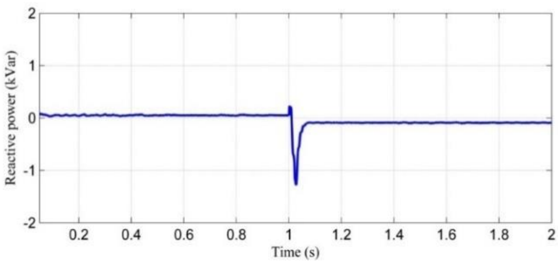

Figure 11. Grid three phase reactive power (kVar)

In Figure 12, it can be observed that the output currents of the converter phases are unbalanced, as the converter delivering unbalanced currents which formed because the active and reactive powers demanded by the unbalanced feeder as illustrated in Table 2. The converter currents decreased in the second sub-period because the P_{ref} is changed from -20 kW during charging the EV to zero when stop charging.

It can be seen in Figure 13 the transformer currents are balanced in both simulation sub-periods because the converter compensates the unbalanced currents which approves the effectiveness of the proposed control strategy. The three-phase currents in the first simulation sub-period are less than the currents of the second sub-period because in the first period the transformer delivers active power of 7 kW to the feeder and in the second period it consumes active power of 13 kW from the grid.

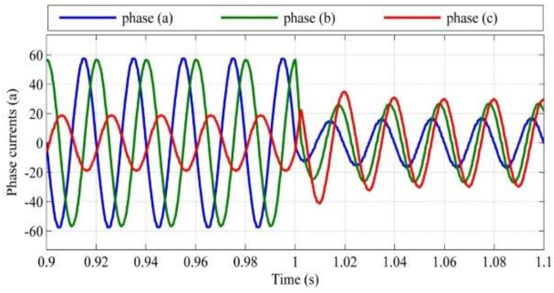

Figure 12. Converter output currents (A)

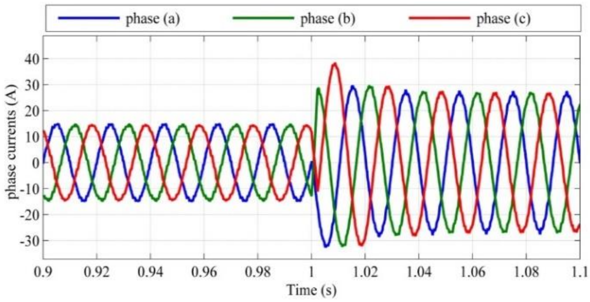

Figure 13. Grid three phase currents (A)

5. CONCLUSION

This paper presents a control scheme for a three-phase four-leg power converter used for DC- EV charging stations. The main function of the proposed converter is to convert AC grid power to DC power required to charge the battery of EVs. In addition to this, the proposed control scheme enables the converter to be used for balancing the unbalanced currents of the distribution transformer, and also for compensating the demanded reactive power. This avoids frequent disconnections of distribution transformer may occur due to unbalanced operation and overload conditions. The considered case study for testing the proposed converter control scheme consists of a distribution feeder with single-phase PV inverters and single-phase loads. The control loops of positive, negative, and zero sequences are explained with their corresponding parameters. The simulation results show that the control strategy is very effective to control the DC power required for charging the electric vehicles and unbalanced mitigation during charging. Moreover, it makes the proposed converter enable for unbalanced mitigation and reactive power compensation during off-charging period which are a possible to occur in the case the EV battery fully charged or the charger not used.

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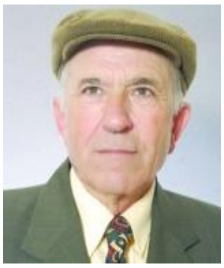

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