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Design of On board charger for Electric Vehicle.

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ABSTRACT
The Auto-motive sector is upgrading itself with new technology and with the theme of being eco-friendly the Electric Vehicles are making their place in this sector. These vehicles are battery fed vehicles and designing a charger that can charge the battery very fast with very little interference to source is required. The PFC circuit is must while designing the charger. For on-board charger the size of the charger should be small and compact meeting the specification specified by the Indian Ministry of Power. Hence a 3-phase, 4-wire vienna rectifier is designed which signifies the advantage of improved Power factor, low power consumption by the switches and also low voltage stress on the switches. This increases the power density of the on-board charger. Firstly the working principle of the Vienna rectifier is designed and a Dual loop PI control is used for the rectifier. The converter is simulated in MATLAB-Simulink and the results prove that the proposed converter is feasible with good dynamic and static performance.

Keywords – Electric Vehicle, On-Board Chargers, PFC, 3-Phase 4-wire Vienna Rectifier, Dual Closed Loop PI control.

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I.INTRODUCTION

The world is moving towards electrification. In recent times, electric vehicles (EV) are gaining popularity, and the reasons behind this are many. The most prominent one is the depletion of fossil fuels and the parallel up-gradation in Automotive Sector. The pollution due to the petroleum vehicles which releases greenhouse gases has been increased. Keeping in mind the up-gradation of the technology and safety of the customers as major concern the automotive sector is moving towards Electrification. Hence, in recent years people are switching to Electric vehicles which have reduced emission of greenhouse gases and easy to operate. The Fuel cost of EV is much lesser than the petroleum vehicles [1].

The Electric Vehicles operate with the power supply from the batteries and these batteries are to be charged on timely basis. There are several types of charging available; there are on-board chargers and off-board chargers. Off-board chargers are the charging stations where the number of vehicles gets charged. Onboard chargers are the one where the charging equipment is in the vehicle itself, and we need to plug-in a connecting cord to charge the battery. There are again 2 types it is battery charging through Alternate current and other through Direct current. The Direct current charging is very fast charging than AC charging, but the available source current is AC, therefore a charger which charges the battery very fast through AC current is required. The AC charging of 2.5KW or 3KW can fast charge the 2-wheelers battery. Hence, the Three-phase AC charger which charges the battery within 1-2 hrs is required for Electric Vehicle 2-wheelers [2].

The chargers and the battery used in the Electric vehicles should be as per the Indian Standards. The standards described by Government of India Ministry of Power gives complete details of Batteries to be used in EV, the Charging specifications, the protection to be taken so that there is energy balance in Grid and the power factor of the is not affected. They also provide the specification to be incorporated in communication protocols. They also specify the connecting cord pins that have to be used in DC charging, single and Three-phase AC charging. The battery charger must be designed as per these Standards [4].

The single phase AC chargers are available in the market, but the charging duration is 6-8hr for 80% of charging, hence 3-phase charger is to be designed. There are several 3-phase chargers available in the market but they are designed based on their own specifications to charge the batteries they use in their application and the specification changes with the change in application of the batteries and with the manufacturer of the chargers. Hence a general Three-Phase AC charger that follows all the specification specified by Indian Ministry is designed. The 3-phase chargers have multiple topologies the three-phase rectifiers. It may be controlled and uncontrolled, but the 3-phase supply must be of 3-phase 4- wire. And the design of the charger and control circuit is based on this topology. With these combinations a 3-phase 4 wire charger has to be designed, which includes a 3-phase rectifier, a PFC corrector, a DC-DC converter and a BMS. The block representation of the charger is showed in Fig.1

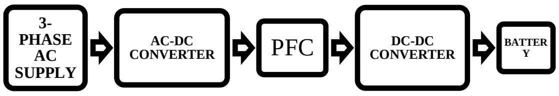

Fig. 1: General Block diagram of 3-phase on-board charger.

AC-DC conversion as very wide application, this can be used as power source for batteries, micro electronics, DC motors etc. The classification of the rectifier is shown in the Fig.2.

By the detailed study of the rectifiers and keeping in mind the cost and efficiency criteria the Three-Phase controlled Rectifiers was most preferable for the charger.[5]-[7].

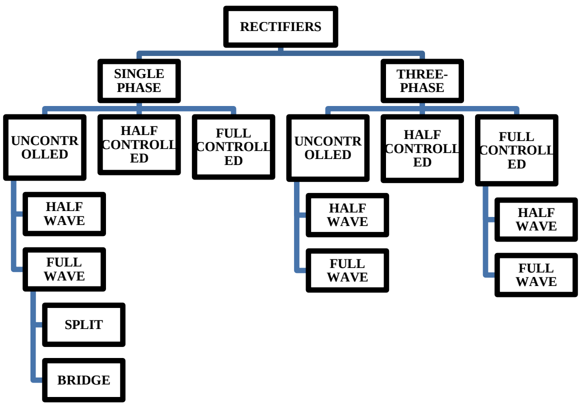

Fig. 2: Classification of Rectifier.

The Power Factor correction is the major concern since the number of electronic devices using switched-mode power supplies increases, power from the grid it varies the power factor of the supply which will be the major cause of disturbance to the grid, this may lead to penalty over the consumer too, hence for every application a power factor corrector is required.

Power factor is defined as the ratio of real input power to the RMS value voltage and current of the load or power factor corrector input.

$$\text{Power Factor}=\frac{Power\ \ input}{V_{rms}\, I_{rms}} \qquad (1)$$

The power factor should be analyzed in terms of the power-line fundamental frequency's harmonic series, and it is defined as,

$$Power\ Factor = \frac{1}{\sqrt{1+THD^2}} \qquad (2)$$

Power-factor correction (PFC) is used to avoid input current harmonics, thereby minimizing interference with other devices being powered from the same source.

In recent time the Vienna Rectifier is gaining attention. It is being a boost rectifier with the significant advantage of high power factor, low voltage stress on each switch. A Vienna Rectifier is nothing but a 3 bidirectional switch rectifier where it features the split output DC rail. [8]-[18].

Designing a rectifier and PFC circuit differently would increase the electronic and the efficiency may compensate, hence with the very basic concepts of PWM rectifier and Boost rectifier the Vienna Rectifier is designed. The Vienna rectifier is used for both rectification and power factor correction purpose. Hence a 3-phase 4 wire Vienna rectifier with dual closed loop PI control is designed here.

Controller: The regulation of the input current in the converter is achieved by adjusting the duty cycle. There are three basic algorithms used they are P, PI and PID. The PI controller which regulate the input current in the Inner current loop, reduce peak over shoot and steady-state error. A proportional controller (kp) reduces the settling time and reduced the error but not eliminated it. An integral controller (ki) will have the effect of eliminating the steady-state error. [20], [21].
This paper presents dual closed loop PI controller and SPWM.

II. 3-PHASE 4 WIRE VIENNA RECTIFIER

A Vienna rectifier was introduced by Professor Johann W. Kolar in 1994. It is one of the popular structures for PFC correction of the rectifier circuit. It is a three-phase, three-levels and three bidirectional switch rectifier; it is kind of PWM (Pulse Width Modulation) rectifier with controlled output voltage. The topology of the Vienna Rectifier is a combination of a boost DC\DC converter with a three-phase diode bridge rectifier. Fig.3. illustrates this rectifier circuit.

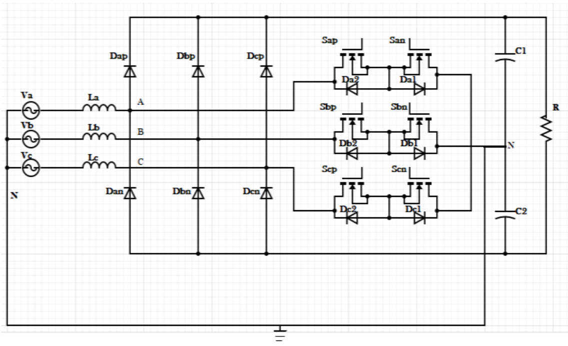

Fig.3: 3-Phase, 4-wire Vienna rectifier

Considering the output to be constant V_{DC} the input current is drawn in 3 levels with respect to output as $V_{DC}/2$, 0, $-V_{DC}/2$.

Due to this there is smaller current ripple and smaller voltage stress on the semiconductor device, therefore switching losses is reduced, filtering effect is reduced and high frequency operation is enabled. This circuit is highly reliable because there can never be Shorting of DC voltage.

The Vienna rectifier overcomes the short comes of the uncontrolled and controlled rectifiers such as low power factor on the grid side, serious distortion of input current on the AC side, which bring a lot of harmonic pollution to the voltage of the public grid. Three –Phase Vienna Rectifier is one of the best circuit topology, the output level increases, the voltage stress on each switch decreases, since only one switch conducts at one cycle. As the output voltage jump decreases the AC-current distortion also decreases.

Fig.4. shows the circuit diagram of the Vienna rectifier. The output capacitor is split into C_1 and C_2 with equal capacitor values, and it is clamped at the neutral point. The voltage across each capacitor is $V_{DC}/2$ and $-V_{DC}/2$, which forms the output voltage of the circuit. Hence 3 level voltage is obtained that is $V_{DC}/2$, 0, $-V_{DC}/2$.The DC bus voltage is assumed to be a constant dc voltage and can be connected to a DC-DC converter to step down the voltage as per the battery requirement.

The input current to the circuit is defined by the voltage across the inductor in each phase. The inductor charges when the switch is ON and discharges when the switch is OFF through positive and negative freewheeling diode depending on the current direction. The existence of an input inductor creates a current source at the input while the capacitors create output voltages.

The Vienna rectifier has three bidirectional switches, and by choosing their (ON\OFF) state considering the polarity of the phase current in each phase, the voltage for each phase will be determined. So, the phase voltage depends on the direction of phase current and switch position. In this topology, the midpoint N is considered as reference point with zero voltage. Therefore, the phase voltage is described as,

If E_N is the neutral voltage the phase voltage of each phase is given by.

$$V_{KN} = E_N - L_k \frac{di_K}{dt} \quad (3)$$

Therefore inductor voltage is given by,

$$L_k \frac{di_K}{dt} = E_N - V_{KN} \quad (4)$$

Where V_{KN} is given by,

$$V_{KN} = \frac{V_{DC}}{2}, \quad S_{Kp}=0 \quad (5)$$

$$V_{KN} = 0, \quad S_{Kp} = 1$$

$$V_{KN} = \frac{-V_{DC}}{2}, \quad S_{Kn}= 0 \quad (6)$$

$$V_{KN} = 0, \quad S_{Kn} = 1$$

Where K= a, b, c.

The Vienna rectifier operation is explained in 4 modes, that is when alternative current is greater than zero, in this state operation when switch is ON and operation when switch is OFF, and when alternative current is lesser than zero or negative, again operation when switch is ON and switch OFF .The explanation is similar with all the three-phases.

Vienna rectifier takes the input in 3 steps, if we consider the output of the rectifier as constant $V_{DC,}$ the rectifier draws input as $+V_{DC}/2$, 0, $-V_{DC}/2$.

Considering only Phase A, the operation of the Vienna rectifier is explained and the operation of the other phases is similar to that of phase A.

Mode 1: When current is positive or greater than zero and the switch is OFF, the current flow is shown in Fig.4. The current flow is from the source, flowing through the freewheeling diode D_{ap} and charges the capacitor C_1 to DC/2, and flows back through the neutral.

Mode 2: When switch is ON the current flows through the switch S_{ap} and diode D_{a1} and flows back through neutral, drawing zero voltage Operation is shown in Fig.5.

Mode 3: When current is negative or less than zero and the switch is on, the current flows from neutral and flows through switch S_{an} and diode D_{a2}, flows back through source completing the loop. The voltage drawn is zero. Operation is shown in Fig.6.

Mode 4: When switch is OFF, the current flows from neutral charges capacitor C_2 to –VDC/2 with respect to line and flows back through freewheeling diode D_{an} back to source completing the loop. Operation is shown in Fig.7.

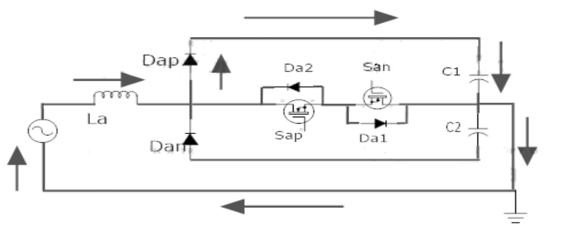

Fig.4: Current flow when $I_a > 0$ and switch is OFF.

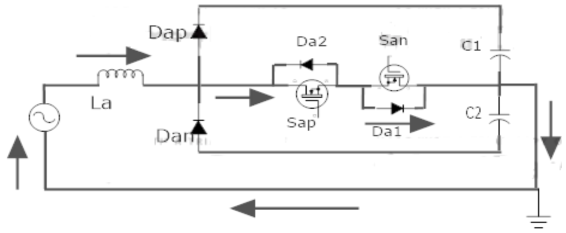

Fig.5: Current flow when $I_a > 0$ and switch is ON.

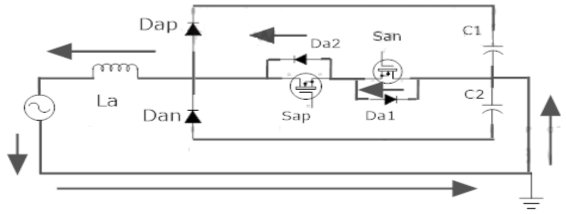

Fig.6: Current flow when $I_a < 0$ and switch is ON.

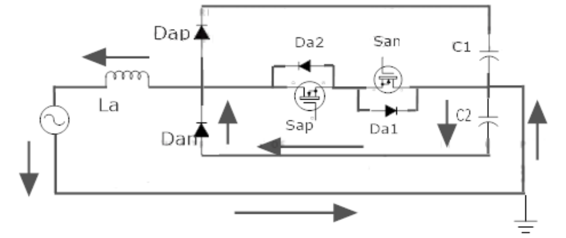

Fig.7: Current flow when $I_a < 0$ and switch is OFF.

In a three phase circuit, the voltage across the phase will have 6 different combinations, that is,

- Va >0, Vb >0, Vc>0.
- Va >0, Vb<0, Vc>0.
- Va >0, Vb >0, Vc <0.
- Va <0, Vb >0, Vc <0.
- Va <0, Vb >0, Vc >0.
- Va <0, Vb >0, Vc <0.

In each condition there are 8 sets of switching combination. The switching combination for the condition Va>0, Vb<0, Vc>0, is given in the Table.1

Table.1: Eight different combination of switching.

S_A		S_B		S_C				
S_{Ap}	S_{An}	S_{Bp}	S_{Bn}	S_{Cp}	S_{Cn}	V_{AN}	V_{BN}	V_{CN}
0	0	0	0	0	0	$+V_{DC}/2$	$-V_{DC}/2$	$+V_{DC}/2$
0	0	0	0	1	0	$+V_{DC}/2$	$-V_{DC}/2$	0
0	0	0	1	0	0	$+V_{DC}/2$	0	$+V_{DC}/2$
0	0	0	1	1	0	$+V_{DC}/2$	0	0
1	0	0	0	0	0	0	$-V_{DC}/2$	$+V_{DC}/2$
1	0	0	1	0	0	0	0	$+V_{DC}/2$
1	0	0	0	1	0	0	$-V_{DC}/2$	0
1	0	0	1	1	0	0	0	0

III. DUAL LOOP PI CONTROL

Many control schemes have been presented for Vienna rectifier with unity power factor. The Vienna rectifier topology is shown in Fig.4.Where the potential of the AC connection points (V_A, V_B, V_C) is under control of the bidirectional switches and the direction of phase currents, and therefore the inductor current can also be controlled by the bidirectional switches according to input voltage and current direction. A dual closed loop PI regulator is designed in order to control the switches of the Vienna rectifier. The Block Representation of the converter with control circuit is shown in Fig.8.

The 3-phase voltages and currents are given by,

Voltage,

$$V_{AS} = V_A$$
$$V_{BS} = V_B e^{j\left(\frac{2\pi}{3}\right)}$$
$$V_{CS} = V_C e^{j\left(\frac{4\pi}{3}\right)}$$

Current,

$$I_{AS} = I_A$$
$$I_{BS} = I_B e^{j\left(\frac{2\pi}{3}\right)}$$
$$I_{CS} = I_C e^{j\left(\frac{4\pi}{3}\right)}$$

The 3-phase voltage and current are transformed to DQ-frame and they are given by,

Voltage,

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} cos\rho & sin\rho \\ -sin\rho & cos\rho \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (8)$$

Current,

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\rho & sin\rho \\ -sin\rho & cos\rho \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (10)$$

Where ρ-angle between abc frame and dq frame.

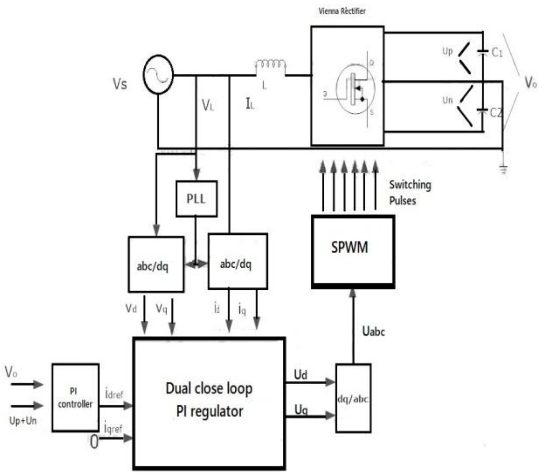

Fig.8: Block Diagram representation of proposed PFC.

The current i_d and i_q corresponds to the active and reactive power so named active power control channel and reactive power control channel respectively.

The outer voltage control loop takes the difference of voltage across two capacitors that should be maintained equal and the output voltage the sum of two capacitor voltages and is fed to a PI regulator. The signal from this PI regulator is fed as the reference signal for active power control. To maintain the reactive power to be zero, the 0 reference is fed to control the reactive power. This forms a single loop shown in Fig.9.

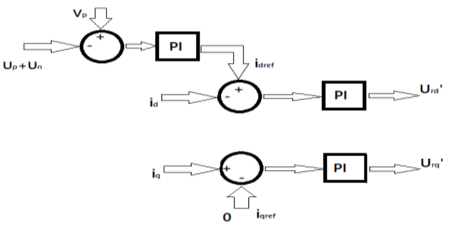

Fig.9: 1st closed loop of PI controller

Now the second loop is framed so that the angle between voltage and current is made zero, hence the U_{rd}' compared with v_d and U_{rq}' with v_q and fed to a PI regulator now the control signals U_d and U_q are transformed to abc-frame as shown in Fig.10. Now this reference signal U_{abc} is compared with the triangular carrier wave of higher frequency to produce the switching pulses for the Vienna rectifier.

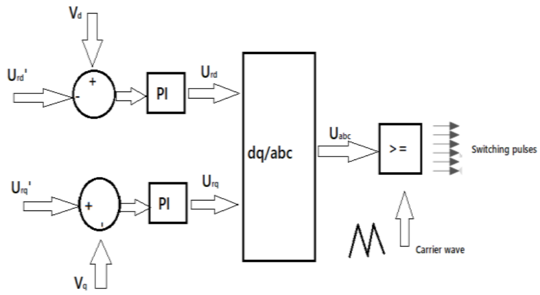

Fig.10: 2nd closed loop of PI controller.

IV. SIMULATION AND RESULTS

The model of Vienna rectifier and double loop PI controller was built based on the previous analysis in MATLAB-Simulink environment. The whole system behavior is considered to be continuous. Three-phase 4 wired supply is used with input line voltage to be 415V and 50Hz. The values of the components used and output specification used are given in Table-2

Table.2: Parameters List.

Parameter	**Symbol**	**Value**
Inductor	L_a,L_b,L_c	15µH
Capacitor	C_p,C_n	1000nF
Resistor	R	20Ω
Output Voltage	V_o	400V
Output Power	P_o	8.5KW

The simulation model in MATLAB-Simulink is as shown in Fig.11.

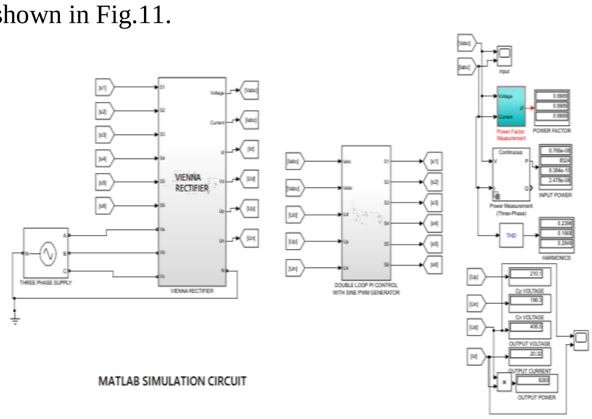

Fig.11: Simulink Model of Vienna Rectifier with PI control.

The output voltage is set to be 400V, and its waveform of output voltage and current is shown in Fig.12.

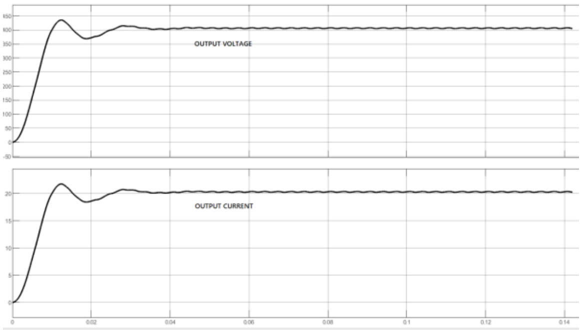

Fig.12: Output voltage and current.

The voltage across the capacitors are shown in Fig.13, the voltage seems to be balanced across two capacitors.

The PI control block is showed in Fig.14, the voltage and the current in DQ-frame are in phase and it is showed in Fig.15.

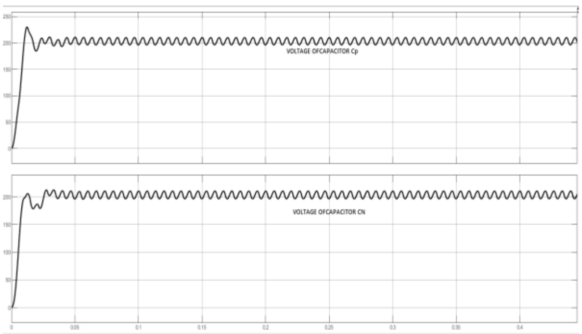

Fig.13: Voltage across Capacitor Cp, Cn.

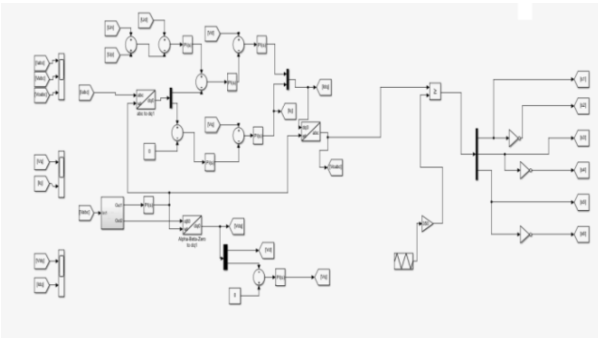

Fig.13: Dual loop PI control.

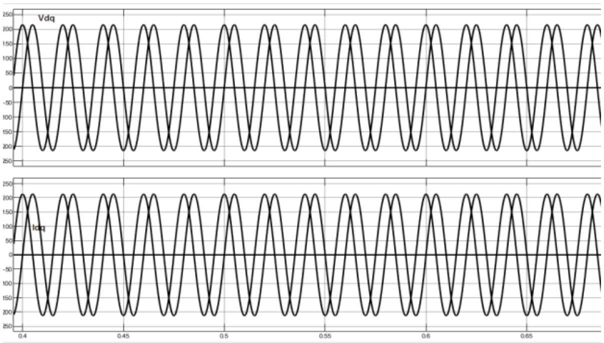

Fig.14: Voltage and current in DQ-frame.

The 3-phase input voltages and current is showed in Fig.15. They both are in-phase. And the voltage and current of single phase in Fig.16.

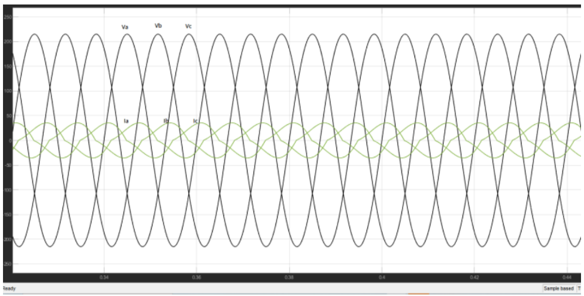

Fig.15: Three-phase input voltage and current

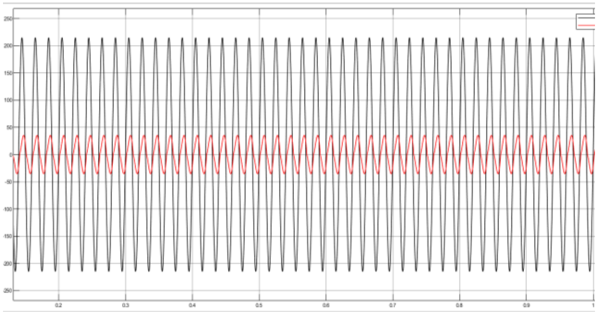

Fig.16: Single-phase input voltage and current

The input power is measured, the power factor is also measured and the THD is also measured. The measured values are showed in Fig.17.

A dc- dc converter has to be designed to bring down the 400V DC to the level of battery that will be connected at the output terminals.

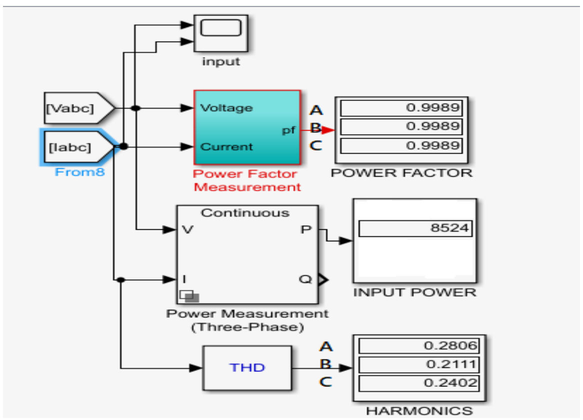

Fig.17. Measured input PF, Power, THD.

V. CONCLUSION

This paper presents 3-Phase 4-wire PFC for EV with PI control is presented. The Vienna Rectifier is used for achieving the Power factor correction and double loop PI controller is used to control the Vienna rectifier. With the use of Vienna rectifier the voltage stress on each device is less since current flows through single switch in each cycle. The double loop PI controller is used achieving dynamic response and power factor correction. The proposed model is simulated in MATLAB-Simulink and verified. The efficiency of the PFC is 95% and PF achieved is 0.9989. The THD of each phase current is 0.28. The output power is 8.5KW, with output voltage 400V.

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