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Design and Control Methods of PFC in Onboard Chargers for Electric Vehicles.

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ABSTRACT
The Electric Vehicles are making their way in Automotive Sector with the up gradation of the technology. To power the EV a battery is needed and this Battery has to be charged frequently, hence an Onboard charger is needed. The onboard charger should contain a PFC circuit so that the supply or the grid is not affected by the harmonics produced by the charger. A 3-phase 4 wire Vienna rectifier is designed as a PFC circuit because of its ability in improving the Power factor, reduction in the power consumption of switches and decrease in the total harmonic distortion of current. Vienna rectifier has the ability to increase the power density specially, in case of high power DC charging. To control the Vienna rectifier a 3-level SVPWM technique is implemented because of is robustness and dynamic response. The same is simulated in the MATLAB-Simulink Environment, the results were analyzed and it proves that the proposed converter is feasible with good dynamic performance and static performance.
***Keywords* -** Electric Vehicle, On-board Chargers, PFC, Vienna Rectifier, 3-level SVPWM.

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I.INTRODUCTION

The Electric Vehicles gaining their prominence in Automotive sector as the technology is improving and the society is moving towards more eco-friendly use of vehicles. These vehicles use Batteries as their source of power supply. The batteries used here are rechargeable batteries, which are charged frequently. Fast charging would be the major criteria while designing the charger for the batteries. DC charging is one of the fast charging techniques employed but for the onboard charger the source available in general is AC, hence a charger to be designed must be of AC charging with fast charging capacity, hence a Three-phase AC source charger is to be designed and it should incorporate the standards described by the Government of India Ministry of Power. According to the Ministry of Power the 3-phase source should be of 3-phase 4-wire system, the efficiency of the charger should be above 95% and PF to be above 0.92. [1-4].

The block representation of general aspects onboard charger is given in the Fig.1. This paper majorly concentrates on the PFC circuit which is to be included in the 3-phase AC onboard charger to maintain the power factor of the input voltage and current so that there is less introduction of harmonics into the grid.

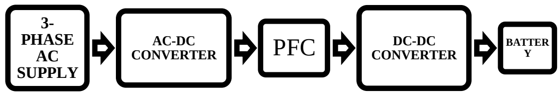

Fig.1: General Block representation of onboard charger.

The PFC circuit is much essential since the electronic devices using switch mode power supplies are increasing. It varies the Power Factor of the supply while consuming the power from the source. This causes major disturbances to the grid and affects the other equipment connected to the same source and may lead to a penalty over the customer too. Hence a PFC is must for every application.
Power Factor is defined as in equation (1)

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

Power Factor can also define as the cosine of the angle between voltage and current. Fig.2 shows that the current and the voltage are perfectly in phase even though there is a severe distortion of the current wave. Applying the "cosine of the phase angle" would lead to a wrong conclusion that this power supply has a power factor of 1.0. Hence, power factor should be analyzed in terms of the power-line fundamental frequency's harmonic series, and it is defined as,

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

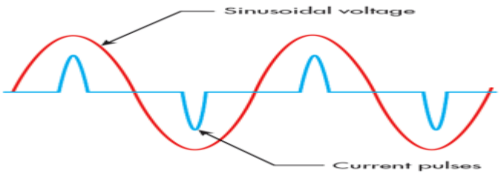

Fig.2. 3-Phase, 4-wire Vienna rectifier

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

A considerable attention is gained by the three-level boost type Vienna rectifier since it has the advantages such as high input power factor, the low voltage stress on each switch and less number of switches employed. The other major advantage of the Vienna rectifier is, both rectification and PF correction can be achieved in a single stage and improves power density of the power system Therefore Vienna rectifier is majorly used in high power DC charging for electric vehicles. [8-18].

The 3-phase source should be of 3-phase, 4-wire supply, therefore a 3-phase 4-wire Vienna rectifier is designed to achieve PFC.

Many control technique is employed to control the Vienna rectifier [19] one of the effective control strategies is found to be SVPWM technique[20], this can increase DC voltage utilization, and quality of the input three phase current also increases. This can solve the neutral point voltage by adjusting the effective time of the redundant vector.[23-26]. The voltage level at the switch is determined by both switch state and current direction hence not all the switch combination can be achieved when SVM is applied. Also DC voltage reduction with less voltage unbalance is achieved with the application of SVPWM which forms the major attraction for industrial applications.

Hence a 3 level SVPWM technique is employed to control the switches of the Vienna rectifier and voltage balance of two capacitors C_p, C_n.

II. 3-PHASE 4 WIRE VIENNA RECTIFIER.

A Vienna rectifier is one of the popular structures for PFC correction of the rectifier circuit. Vienna Rectifier is a 3phase, 3-level, 3 bidirectional switch rectifier where it features the split output DC rail. The Rectifier is a combination of a boost DC\DC converter with a three-phase diode bridge rectifier. Fig.4. illustrates this rectifier circuit. The circuit topology is shown in Fig.2.

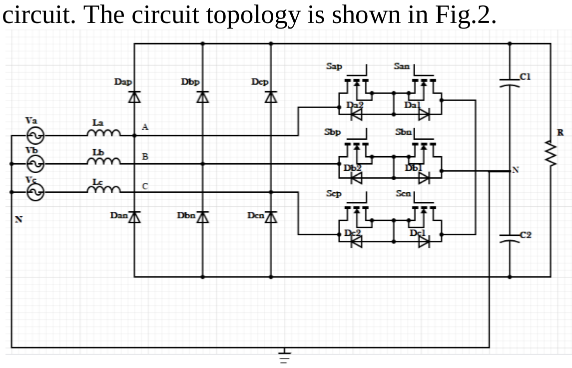

Fig.3. 3-Phase, 4-wire Vienna rectifier

The Vienna rectifier has three bidirectional switches, and by choosing their (ON\OFF) state and the polarity of the phase current in each phase, the voltage for each phase will be determined. If the output voltage is considered to be constant V_{DC} the input current is drawn in 3 levels with respect to output as $V_{DC}/2$, 0, $-V_{DC}/2$.

The operation of the Vienna rectifier is explained considering phase A and the operation of the other phases is similar to that of phase A.

Mode 1: When the switch S_{ap} is OFF and the phase current is greater than zero, the current flows through the freewheeling diode D_{ap}, as shown in the Fig.4. and charges the capacitor C_1 , and flows back through neutral. Since only one diode conducts power loss is less.

Mode 2: When the switch is ON the current takes the low resistant path and flows through the switch S_{ap} and diode D_{a1} and flows back through neutral. The Operation is shown in Fig.5. In this cycle also the resistance offered is only by the diode D_{a1} hence the power loss is less.

Mode 3: When the current is less than zero and the switch S_{an} is ON, the current flows in the reverse direction that is from neutral and flows through switch S_{an} and diode D_{a2}, flows back through source completing the loop. The Operation is shown in Fig.6. Here too the loss occurs only in the diode, hence low loss.

Mode 4: When the current is less than zero with switch S_{an} to be OFF, then current from the neutral flows through freewheeling diode D_{an} to source.

Hence loss is only from the diode The Operation is shown in Fig.7.

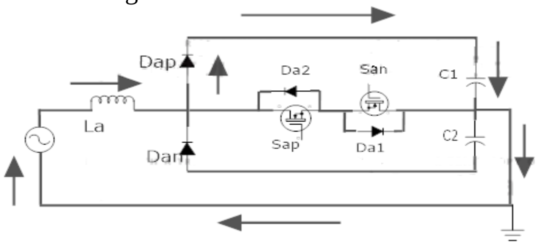

Fig.4. Current flow when $I_a > 0$ and switch is OFF.

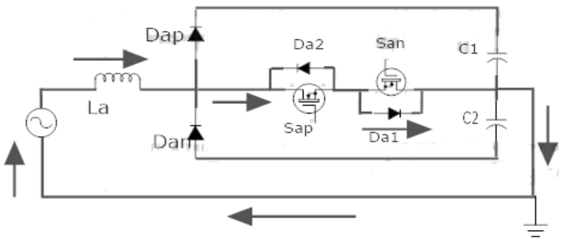

Fig.5. Current flow when $I_a > 0$ and switch is ON.

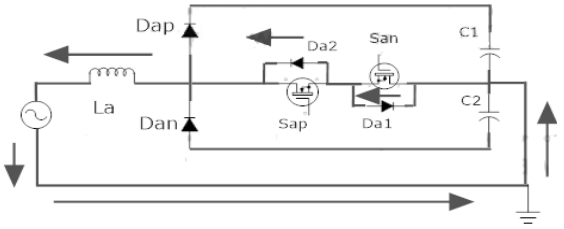

Fig.6. Current flow when $I_a < 0$ and switch is ON.

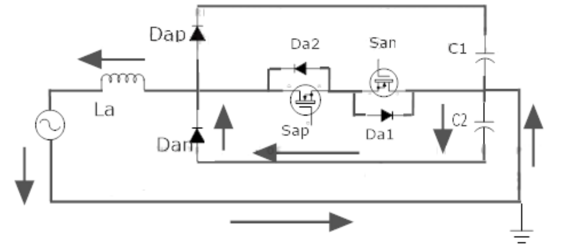

Fig.7. Current flow when $I_a < 0$ and switch is OFF.

III. DUAL LOOP PI CONTROL

Different control strategies are employed for voltage PWM rectifiers. Here Voltage oriented control scheme is used which guarantees a fast and dynamic response.Fig.9. Represents the proposed PFC, the dual close loop control system with decoupled feed-forward control is shown in Fig.10.

The three phases Voltage and current are transformed into DQ-frame. The outer voltage control loop is formed by feeding back the difference between the output voltage and the sum of the voltage across 2 capacitors feeding to a PI controller

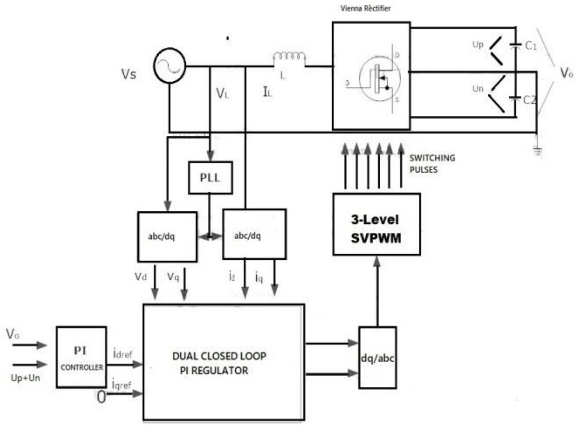

Fig.9. Block representation of proposed PFC.

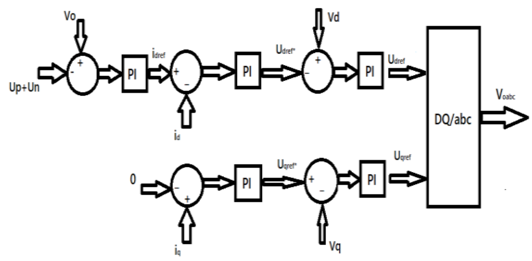

Fig.10. Dual Closed Loop PI regulator

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 signal from the PI controller 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 generates this control signal U_{dref}^*, U_{qref}^*.

For zero angle between voltage and current, hence the U_{dref}^* compared with V_d and U_{qref}^* with V_q and fed to a PI regulator now the control signals U_{ref} and U_{ref} are obtained and are transformed back to abc-frame. This reference voltage V_{oabc} is sent to SVPWM controller in order to generate PWM pulses for the Vienna rectifier.

IV. SPACE VECTOR PULSE WIDTH MODULATION

Many control schemes have been presented for the Vienna rectifier with a unity power factor. The Vienna rectifier topology is shown in Fig.3.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 the input voltage and current direction. A simple 3-level SVPWM technique is suggested here in to control the switches of the Vienna Rectifier.

4.1 Space Vector Pulse width Modulation:

Space Vector Modulation (SVM) is one of the principles, used for the generation of PWM pulses. This technique is employed for the three-phase inverter, but the technique can be adopted for the rectifier too. SVPWM can be implemented for 2 phase system, and can be extended for poly-phase system. Some of the features of this method that have made it very popular three-phase PWM generation method are,

- It is inherently suitable for the digital platform.
- The switching losses are lesser then sinusoidal PWM, since switching frequency of the inverter switch is half the carrier frequency.
- It provides lower harmonics.
- High efficiency.

In SVPWM approach the 3 rotating voltage vectors are represented by a spatial co-ordinate vector called voltage space vector

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

The 3- space components can be represented by single equivalent vector, called resultant space vector V_S, which is given by Equation (4).

$$V_S = V_A + V_B e^{j\left(\frac{2\pi}{3}\right)} + V_C e^{j\left(\frac{4\pi}{3}\right)} \quad (4)$$

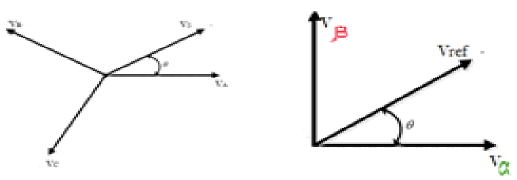

Fig.11. abc- frame and αβ-frame

For the implementation of SVPWM technique the 3 phase voltage vector is represented in the orthogonal frame as shown in Fig.11. The 3-phase voltages are transformed into αβ-frame and are given in Equation (5).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad (5)$$

The Rotating reference Space vector is given by Equation (6).

$$V_{ref} = \sqrt{{V_\alpha}^2 + {V_\beta}^2} \quad (6)$$

4.2 3-level Space Vector Pulse Width Modulation:

The 3-level SVPWM technique is used to control the switches of the Vienna rectifier. In 3-level SVPWM there are 27 vectors, as shown in Fig.12. since in 3-phase, all the 3-phase current will be lagging or leading from each other with certain angle, hence vector [1, 1, 1] and [-1 -1 -1] is eliminated. Hence 25 vectors are the subset of 27 vectors. These vectors frame the hexagon as shown in Fig.12.

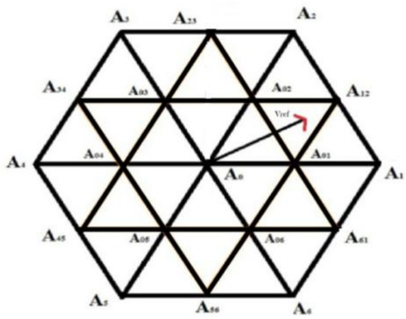

Fig.12: Space Voltage Vectors.

The vectors in 3-level SVPWM are segregated into large vectors, medium Vectors, small vectors and null vectors. The vectors are given in the Table.1.

4.2.1 Sector Selection:

Based on the reference vector position the entire operating region is divided into 6 sectors. Taking the base on 0^0 if the rotating reference space vector's angle, the 6 sectors are classified as shown in the Table.2.

4.2.2 Region selection:

Each sector is further divided into 4 regions. There are 6 sets of vectors that operate in each sector. Each region has 3 vectors which operate for certain time interval in order to obtain the reference voltage vector. There are 4 regions as shown in Fig.13. If the reference vector lies in region 1, V_{ref} is the resultant vector of A_0, A_{01}, A_{02}, similarly in region 2 V_{ref} is the resultant vector of A_{01}, A_1, $A_{12,}$ in region 3 V_{ref} is the resultant vector of A_{01}, A_{02}, A_{12} and in region 4 V_{ref} is the resultant vector of A_{02}, A_{12}, A_2.[31].

Table.1: Space Vectors.

	Sap	San	Sbp	Sbn	Scp	Scn
Null vector						
A_0	0	1	0	1	0	1
	1	0	1	0	1	0

Small Vector						
A_{01+}	1	0	0	0	0	0
A_{01-}	0	0	0	1	0	1
A_{02+}	0	0	0	0	0	1
A_{02-}	1	0	1	0	0	0
A_{03+}	0	1	0	0	0	1
A_{03-}	0	0	1	0	0	0
A_{04+}	0	1	0	0	0	0
A_{04-}	0	0	1	0	1	0
A_{05+}	0	1	0	1	0	0
A_{05-}	0	0	0	0	1	0
A_{06+}	0	0	0	1	0	0
A_{06-}	1	0	0	0	1	0

Large vectors							
A_1=A_2=A_3= A_4=A_5= A_6	0	0	0	0	0	0

Medium vectors						
A_{12}	0	0	0	1	0	0
A_{23}	1	0	0	0	0	0
A_{34}	0	0	0	0	0	1
A_{45}	0	0	1	0	0	0
A_{56}	0	1	0	0	0	0
A_{61}	0	0	0	0	1	0

Table.2: Sector Selection.

Angle	Sector
0^0-60^0	Sector-1
60^0-120^0	Sector-2
120^0-180^0	Sector-3
180^0-240^0	Sector-4
240^0-300^0	Sector-5
300^0-360^0	Sector-6

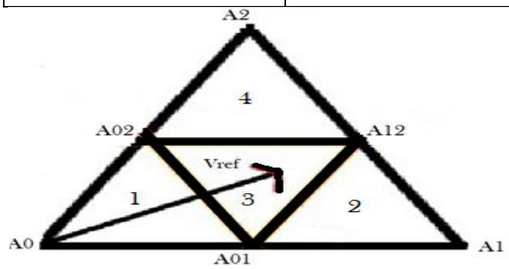

Fig.13: Regions.

In order to find the region where the reference vector lies in a sector, it is assumed that the amplitude of the reference vector fits within the hexagon. The sides of the triangular regions have lengths equal to unity as shown in Fig.14.(a) The reference vector m_n is decomposed into two vectors m_1 and m_2 along with the zero and sixty degrees axes as shown in Fig.14.(b). The sides, p, q and r are the extended projections made to ease the calculation of the values m_1 and m_2.

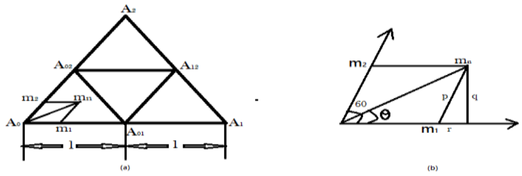

Fig.14. Region Segregation

Apply sine rule to find m_1 and m_2,

$$\frac{p}{\sin\frac{\pi}{2}} = \frac{q}{\sin\frac{\pi}{3}} \quad (7)$$

$$p = m_2 = q * \frac{2}{\sqrt{3}} \quad (8)$$

From the triangle of sides q, m_n, $m_2 + r$ of Fig.(b).

$$q = m_n \sin\theta \quad (10)$$

$$\therefore m_2 = \frac{2}{\sqrt{3}} m_n \sin\theta \quad (11)$$

$$m_1 = m_n \cos\theta - r \quad (12)$$

$$r = p\cos\frac{\pi}{3} \quad (13)$$

$$m_1 = m_n \cos\theta - p\cos\frac{\pi}{3} \quad (14)$$

$p = m_2$

$$m_1 = m_n \cos\theta - \frac{2}{\sqrt{3}} m_n \sin\theta * \cos\frac{\pi}{3} \quad (15)$$

$$\therefore m_1 = m_n(\cos\theta - \frac{\sin\theta}{\sqrt{3}}) \quad (16)$$

The value of m1 and m2 is taken as the duty cycle of the vectors to produce the reference vector. Table.3. summarizes the region segregation in a sector, the same procedure can be implemented for the other sectors.

Table.3: Region Selection.

Condition	Region
$m_1 <= 1$ $m_2 <= 1$ $m_1 + m_2 <= 1$	1
$m_1 > 1$	2
$m_1 <= 1$ $m_2 <= 1$ $m_1 + m_2 > 1$	3
$m_2 > 1$	4

The sequence of selecting the voltage vector in each region and sector is shown in the Fig.15.

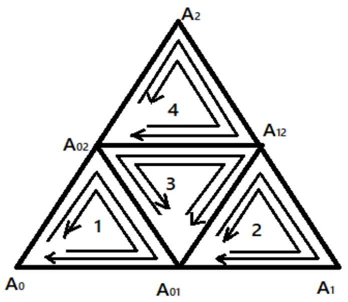

Fig.15: Switching Sequence.

4.2.3 Timing Calculation:

The time duration of the reference vector in each region of a sector is calculated with the assistance of volt time relationship in Equation (17). Consider the reference vector is in region 1, the three nearest vectors are A_0, A_{01} and A_{02}.

$$V_{ref} T_s = A_0 T_0 + A_{01} T_a + A_{02} T_b \tag{17}$$

Where,

$T_S = \frac{1}{F_S}$; F_S =Switching frequency.

$T_a = T_S \left[V_\alpha - \left(\frac{V_\beta}{2h} \right) \right]$

$T_b = T_S \left(\frac{V_\beta}{2h} \right)$

$T_0 = T_S - T_a - T_b$

$h = \frac{\sqrt{3}}{2}$; h= height of the triangle

All small vectors can be implemented with 2 switching states as shown in the table. Therefore in region 1 and region 3 there are 5 switching states to be executed and in region 2 and region 4 there are 4 switching state to be executed. The timing diagram in region 1 and region 3 is shown in Fig.16, and region2 and region 4 in Fig.17.

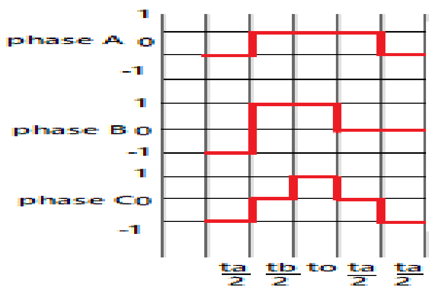

Fig.16: Timing diagram of Region-1 and 3.

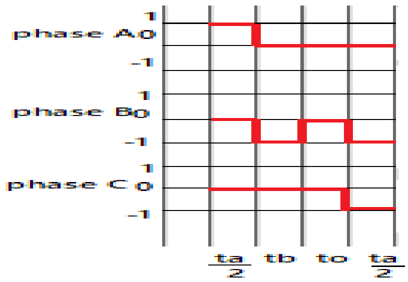

Fig.17: Timing diagram of Region-2 and 4.

For region 1 and region 3 the timing equation is given by,

$$T_s = \frac{T_a}{2} + \frac{T_b}{2} + T_0 + \frac{T_a}{2} + \frac{T_b}{2} \tag{18}$$

For region 2 and region 4 the timing equation is given by,

$$T_s = \frac{T_a}{2} + T_b + T_0 + \frac{T_a}{2} \tag{19}$$

This gives the proper on-off time for the switches in the rectifier.

IV. SIMULATION AND RESULTS

The Vienna rectifier with a 3-level SVPWM control technique model was built in MATLAB-Simulink environment. The behavior is considered to be continuous. Three-phase 4 wired supply is used with an input line voltage to be 415V and 50Hz. The specifications used are given in Table-4.

Table.4: 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	280V
Output Power	P_o	4KW

Fig.18. shows the simulation model in MATLAB-Simulink .

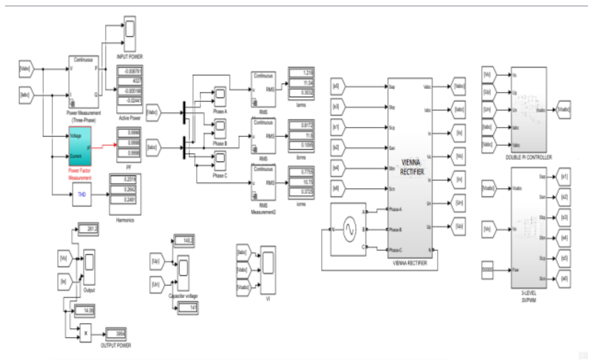

Fig.18: Simulink Model of Vienna Rectifier with SVPWM Control.

The constant output voltage is set to be 280V, and the waveform of output voltage and current is shown in Fig.19.

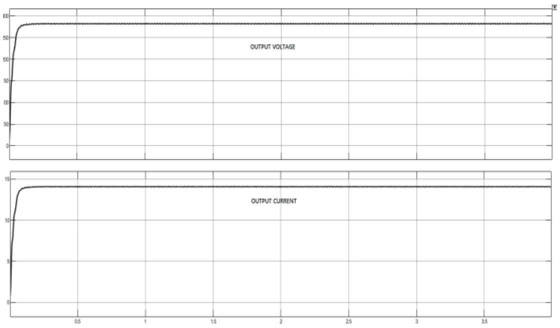

Fig.19: Output voltage and current.

The voltage across the capacitors are shown in Fig.20, the voltage is balanced across two capacitors

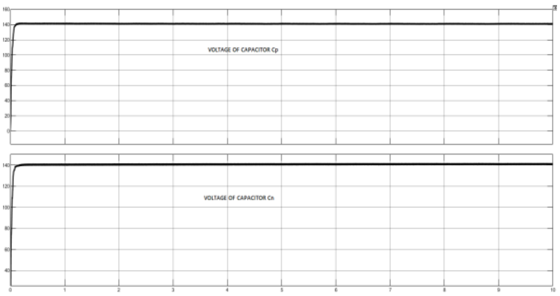

Fig.20: Voltage across Capacitor Cp, Cn.

The sector and region segregation obtained with the application of 3-level SVPWM technique is given is given in Fig.21.

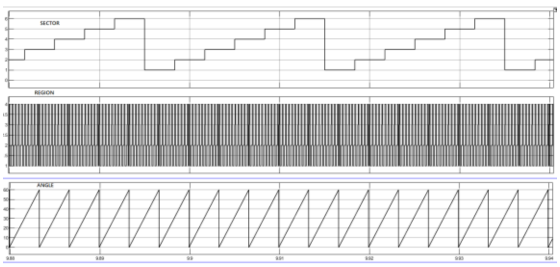

Fig.21: Sector and Region Segregation

The 3-phase input voltages and current are showed in Fig.22. They both are in-phase. And the voltage and current of single phase in Fig.23.

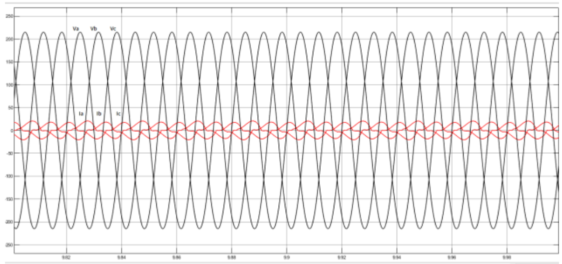

Fig.22: Three-phase input voltage and current.

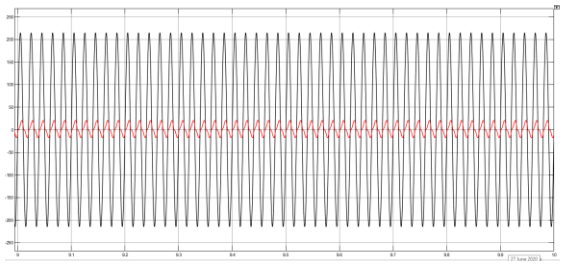

Fig.23: Single-phase input voltage and current.

The input power is measured, the power factor is also measured and the THD is also measured. The measured values are showed in Fig.24. The RMS value of each phase is given in Fig.25.

To step down the 280V DC voltage to the level of the battery that will be connected at the output, a DC-DC converter is to be designed.

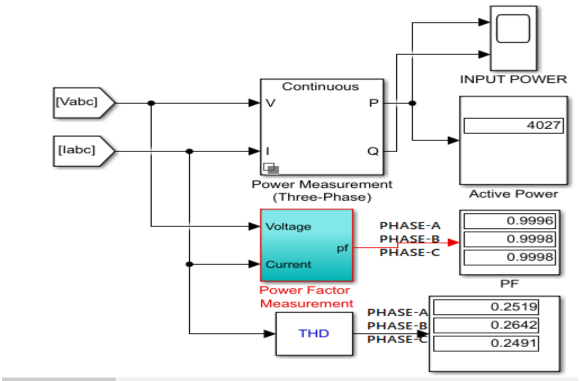

Fig.24: Measured PF, input Power and THD.

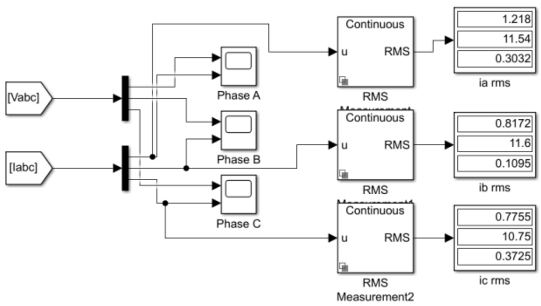

Fig.25: Measured RMS Current.

V. CONCLUSION

This paper presents 3-Phase 4-wire PFC for EV with 3-level SVPWM control. The Vienna Rectifier is used for achieving PF of 0.9989 with SVPWM control. With the use of the Vienna rectifier the voltage stress on each device is less since current flows through a single switch in each cycle. The 3-level SVPWM control technique aids in achieving dynamic response and power factor correction. The proposed model is simulated in MATLAB-Simulink and verified. The efficiency of the PFC is 99% and PF achieved is 0.9989. The THD of each phase current is 0.25. The output power is 4KW, with output voltage 280V.

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