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Vienna Rectifier with Proposed Synchronous Reference Frame Control Theory for Power Quality

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Abstract:- In this paper, three phase Vienna rectifier (VR) topology with sinusoidal input currents and controlled output voltage has been compared with various rectifiers. A comparative study of three different rectifiers have been compared with Vienna rectifier by parameters like switching loss, conduction loss, power density etc. Performance of Vienna rectifier with proportional integrating and derivative control method (PID control), Hysteresis control method and fuzzy logic control method have been analyzed here by parameters like Total Harmonics Distortion (THD) and Power factor (PF) along with various Load conditions. First time we have proposed synchronous reference frame (SRF) for control of Vienna rectifier. Results of Simulink model of proposed SRF control theory has been compared with PID control, hysteresis control and fuzzy logic control methods. We have tried to suggest proposed SRF control method is better among them to improve performance of Vienna rectifier.

Keywords*:* Vienna Rectifier(VR), proportional integrating and derivative control method (PID control), Total Harmonics Distortion (THD) , synchronous reference frame theory (SRF), Power Factor (PF) .

I. Introduction

Three level rectifiers have been paid much attention in the development of new energy generation due to its advantages such as high voltage class, high power factor and low switching loss. The Vienna rectifier is a unidirectional boost type improved power quality three level rectifier. The Vienna rectifier is the best choice for high-power applications because it helps to increase output voltage while reducing ripple and improving current efficiency. A major advantage of three levels characteristic is that for the selection of the blocking voltage capability of the power switch is only half of the peak value of the line-to-line voltage and not the total value is relevant. Due to lower switched voltage, a lower conducted EMI noise level results. Furthermore, due to higher number of levels the difference between fundamental neural current and ripple neural current remains limited to smaller value which results reduction in value of boost inductance requirement [5]. The comparison and evaluation of these some most popular converters are presented, analyzed, and compared in terms of conduction loss, switching loss, power density, power factor, and total harmonic distortion. Based on review, it has found that the Vienna rectifier is the best suitable converter topology for the high-power DC, for its low switching loss, low conduction loss and high-power density [2].

II. Working Principle and Scope Of Vienna Rectifier

The operation and control of the Vienna rectifier is different from conventional two level active front end rectifiers. This rectifier has three level operation using three switches that lead to imbalance of DC voltage across the two output leads to imbalance of DC voltages across the two output capacitor. The most popular SPWM, SVPWM, trapezoidal PWM and PWM using Hysteresis method has been implemented and analyzed for performance improvement of Vienna rectifier. The control of three active semiconductor devices ensures sinusoidal input current, desired output voltage and balance capacitor voltage. A Vienna rectifier consists of three switches and eighteen diodes. The schematic diagram of the Vienna rectifier is shown in Fig (1). The main components in the Three-level Vienna rectifier topology are three Boost inductors, three power bridge arms, and two DC side capacitors in series. Each power bridge arm consists of two

Reverse series switches and a power switch that allows two-way current flow.

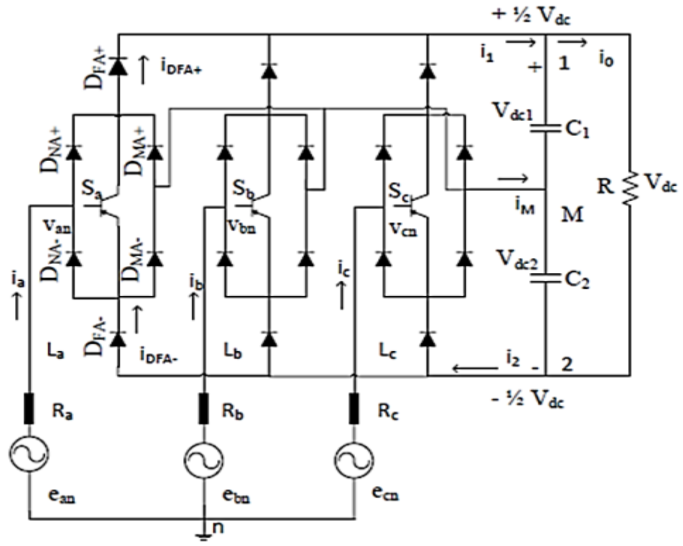

Fig. 1 A Schematic Diagram of Vienna Rectifier

The terminal voltage of Vienna rectifier depends on switching state as well as polarity of the input AC current. Three phase generation side voltages can be represented as;

$$e_{an} = e_m \sin(\omega t) \qquad \dots (i)$$

$$e_{an} = e_m \sin(\omega t + 120°) \qquad \dots (ii)$$

$$e_{an} = e_m \sin(\omega t - 120°) \qquad \dots (iii)$$

The terminal voltage of the rectifier depends upon on the switching states of switches and polarity of input currents. Terminal voltage as a function of current polarity and switching states can be expressed as

$$V_{an} = (V_{dc}/2)\, Sign\, (i_a)\, (1-S_a) \qquad \dots (iv)$$

$$V_{bn} = (V_{dc}/2)\, Sign\, (i_b)\, (1-S_b) \qquad \dots (v)$$

$$V_{cn} = (V_{dc}/2)\, Sign\, (i_c)\, (1-S_c) \qquad \dots (vi)$$

Where sign of phase current positive for positive cycle and Negative for Negative cycle. The switches S_a, S_b and S_c are switching states of the switches (S_a,S_b,S_c = 1 when switches are ON and S_a,S_b,S_c =0 when switches are OFF. It is clear that output DC may be ± $V_{dc}/2$ for any particular case. Moreover with comparison with other PFC like Front end converter SWISS rectifier the Vienna rectifier has been found more advantageous with following technical points. In the three-phase three-wire system, assuming the three-phase input voltage is balanced, the sum of the three-phase AC input current is 0, so there are six three-phase current states in the Vienna rectifier circuit. Therefore, it can be divided into six sectors, each of which has an interval of 60°, and the current polarity is fixed within each sector. At a certain current polarity moment, φ = (- 30° , +30°), the three-phase bridge arm has different switching state combinations, so that the potential at the input end of the rectifier can be 0, $V_{dc/2}$, or $-V_{dc/2}$. Here, in Sector 3 with an interval of 120°~180° is selected as an example. The potential at the input end of the rectifier under 8 different switch combinations is shown in Table I

Table I : Output of each phase in all switching combinations in Vienna foe 120°~180°

Switch S_a	Switch S_b	Switch S_c	Output Phase A	Output Phase B	Output Phase C
0	0	0	$V_{dc/2}$	$V_{dc/2}$	$-V_{dc/2}$
0	0	1	$V_{dc/2}$	$V_{dc/2}$	0
0	1	0	$V_{dc/2}$	0	$-V_{dc/2}$
0	1	1	$V_{dc/2}$	0	0
1	0	0	0	$V_{dc/2}$	$-V_{dc/2}$
1	0	1	0	$V_{dc/2}$	0
1	1	0	0	0	$- V_{dc/2}$
1	1	1	0	0	0

Summarised all above discussion, following points shows significance for Vienna rectifier

- Less number of switches required in Vienna rectifier. As the number of switches is lower, switching frequency for PWM control is higher compare to front end. So required filter is less compare to front end. Power density improved.
- It is a three-level rectifier. A major advantage of the three-level characteristic is that for the selection of the blocking voltage capability of the transistor switch only half of the peak value of the line-to-line voltage. As a result of the lower switched voltage, a lower conducted EMI noise level is generated.
- Conduction losses are those voltage and current products that occur when a power switch or a rectifier is conducting current. This is duty-cycle dependent. Due to low number of switches, it can be used for high the switching frequency. Higher frequency operation leads lower conduction loss.
- Switching losses occur when the power switch or rectifier is transitioning between the ON state to the OFF state and vice versa. Among above rectifier's type, Vienna rectifier has minimum number of switches in circuit for operation. Due to this switching complexity is lower and we can go for higher switching frequency operation compare to other topologies. Higher frequency operation results in power density Secondly switch ratting is also half compare to other topology. It means higher ON state resistance of switch will going to increase switching loss compare to Vienna rectifier.

III. Switching and Conduction Loss Comarative Analysis Of Vienna Rectifier

Power loss calculation of switching devices in converters is important as it predicts the system efficiency and provides a reference for analysis. Two main type of losses are the conduction and switching losses, which would be analyzed for switches and diodes. Leakage losses are not considered here for the sake of brevity.

A. Conduction power losses

Equivalent circuit of a switch during ON state comprises of two elements connected in series, a temperature dependent resistor and a DC voltage source. Let (U0) and (R_I) are the zero current voltage depicted as (Vsw) and the ON state resistance respectively at a given temperature. The instantaneous conduction losses can thus be given as

$$Pc(t) = Uo\ ic(t) + Ri\ ic^2(t) \qquad ……(vii)$$

Integrating the above equation over one switching time period Tsw gives the average conduction loss.

$$Pc\ avg = \frac{1}{Tsw}\int_0^{Tsw}\left(Uo\ ic(t) + Ri\ ic^2(t)\right)dt.. \qquad ....(viii)$$

$$Pc\ avg = Irms^2\ .Ri + Uo\ Iavg \qquad .....(ix)$$

The conduction losses in a PWM converter depends on power factor (φ) as well as modulation index M. The conduction loss for a single IGBT switch using PWM (THI) is explained in [10][11] and can be expressed as,

$$Pc\ ,sw = Uo\ Ipeak\left(\frac{1}{2\pi} + \frac{\pi}{8}M\ cos\varphi\right) + Ri\ ip^2\left(\frac{1}{8} + \frac{M}{3\pi}\cos\varphi - \frac{M3}{15}\cos 3\varphi\right) \qquad ....(x)$$

where M3 is the amplitude of third harmonic and is selected as 1/6 for improving DC link utilization.

B. Switching power losses

The switching energy losses Eon and Eof f can be determined from the plots given in the data sheets by the manufacturer. These parameters are proportional to the current iC and off state voltage Udc across the IGBT [8][9]. The instantaneous value of the Energy losses are given as,

$$Eon = \frac{Udc}{Uref}\cdot\frac{Ic}{Iref}.Eon,ref \qquad .....(xi)$$

$$Eoff = \frac{Udc}{Uref}\cdot\frac{Ic}{Iref}.Eoff,ref \qquad .... (xii)$$

The average value can be determined by integrating eq. 11 and 12 over one time period as,

$$Eon\ avg = \frac{1}{2\pi}\int_0^{\pi}\frac{Udc}{Uref}\cdot\frac{Ic}{Iref}.Eon,ref\ \ d\omega t......(xiii)$$

$$Eon\ avg = \frac{\sqrt{2}}{\pi}\frac{Udc}{Uref}\cdot\frac{Ic}{Iref}.Eon,ref\ .....(xiv)$$

Similarly,

$$Eoff\ avg = \frac{1}{2\pi}\int_0^{\pi}\frac{Udc}{Uref}\cdot\frac{Ic}{Iref}.Eoff,ref\ \ d\omega t......(xv)$$

$$Eoff\ avg = \frac{\sqrt{2}}{\pi}\frac{Udc}{Uref}\cdot\frac{Ic}{Iref}.Eoff,ref\ .....(xvi)$$

The total switching losses can be given as,

$$Psw = (Eon + Eoff).fsw \qquad ...(xvii)$$

With the relative switch on time (duty cycle) and input current and/or output current , the instantaneous conduction states of power semiconductors are defined and average current values can be calculated by averaging over a pulse period. Based on that , average and root mean square (rms) values of the current of interest can be determined by averaging over the main period. The resultant equation of individual topologies is complied in Fig 4 to Fig 7. The parameter modulation index M , represents the ratio of the amplitude of the phase voltage/current on ac side and the dc output voltage and/or dc output current. [3]

$$M = \frac{\sim Im}{Im} \qquad ... \qquad .. \qquad (xi)$$

Where ~Im represent amplitude of phase ac current or voltage of fundamental component in ON time and Im represents dc currents ON time.

The calculation of various currents for modulation index M= amplitude of fundamental phase current / average DC output current = 0.5 has been considered for reference and resultant different current are summarised in table below for above reference paper.[3]

Table II : summary of losses for various converters topology for modulation index M=0.5

Current Stress	**Front end Boost (6D+6S)**	**Front end Buck (6D+6S)**	**Swiss (14D+4S)**	**Vienna Rectiifier (18D+3S)**
Is (switch)	3.06	3.46	3.21	0.568
Id (Diode)	2.66	3.96	3.38	2.92
Total stress	5.72	7.42	6.59	3.488
Conduction loss	Moderate	Moderate	Maximum	Minimum

IV. Synchronous reference frame theory

The block diagram for synchronous reference frame theory is mentioned in Fig 2. In synchronous reference frame theory the three phase currents or voltages are converted to its equivalent two dimensions. i.e. dq transformation. Then using low pass filter we are able to get its fundamental component. This fundamental component is subtracted from its harmonics + fundamental component. It results harmonic component of voltage or current. The equation which converts abc to αβ parameter is given by equations are as below,

$$V\alpha = 0.473Va - 0.407Vb - 0.407\,Vc \ldots\ldots \text{(xii)}$$

$$V\beta = 0Va - 0.7Vb + 0.7Vc \ldots\ldots \quad \text{(xiii)}$$

From αβ to dq transformation can be obtained by following equations,

$$Vd = cos\omega t * V\alpha - sin\omega t * V\beta \ldots\ldots \quad \ldots\text{(xiv)}$$

$$Vq = sin\omega t * V\alpha + \cos\omega t * V\beta \ldots \quad \ldots\ldots\text{(xv)}$$

This will separate out fundamental and oscillating components. These signals are passing through low pass filter which is designed for fundamental component and suppressed harmonic component. These signals are passed through dq to αβ and then αβ to abc for getting fundamental component of source phase current components. The following equations are used to find αβ to abc parameter and fundamental components,

$$Vf\alpha = cos\omega t * Vsd + sin\omega t * Vsq \ldots\ldots \quad \text{(xvi)}$$

$$Vf\beta = -sin\omega t * Vsd + cos\omega t * Vsq \quad \ldots \quad \text{(xvii)}$$

$$Vfa = 0.471\,Vf\alpha \quad \ldots \quad \text{(xviii)}$$

$$Vfb = -0.235\,Vf\alpha - 0.408Vf\beta \ldots \quad .\text{(xix)}$$

$$Vfc = -0.235\,Vf\alpha + 0.408Vf\beta \ldots \quad .\text{(xx)}$$

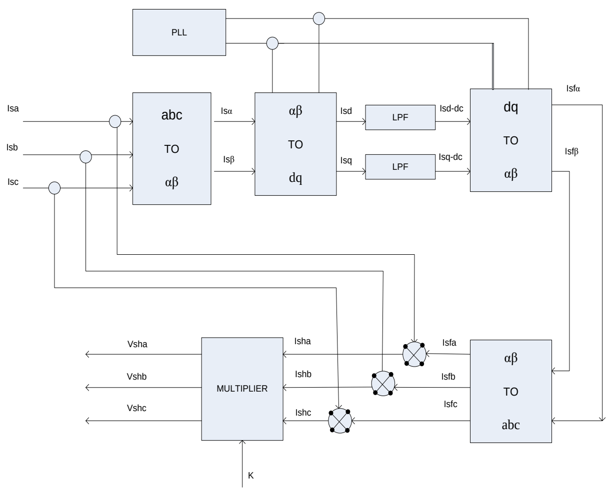

Fig. 2 Block diagram of SRF control theory

Earlier most of the control theories PID control method, Hysteresis control method, Fuzzy logic control method have been implemented in Vienna rectifier for reducing current harmonics and power factor correction. By considering advantages of Vienna rectifier and SRF control technique, proposed SRF theory for generation of control pulses for Vienna rectifier switches has been introduced here. Performance analysis of Vienna rectifier with SRF theory has been attempted by MATLAB simulation for various load condition. Simulation of Vienna rectifier of proposed SRF control has been compared with hysteresis and PI control method and results are summarized for conclusion.

V. Matlab Simulation of Vienna Rectifier with Proposed SRF control Theory

The MATLAB/ Simulink model data are presented here is proposed SRF control theory for Vienna rectifier performance individually. The overall performance comparison is given in Table 2. The DC output of 200 V for 230 V fundamental frequency of 50 Hz input were taken for simulation. Various popular control techniques have been implemented like PID control method, Hysteresis control method and fuzzy logic control method have been simulated using MATLAB simulink model for Vienna rectifier with different load conditions have been simulated and has been compared with proposed SRF control theory. THD and PF have been measured for all four techniques. The performance of Vienna rectifier has been concluded by analysis of variation in THD and PF. MATLAB simulink model for various control techniques have been shown in fig 3 to fig 6

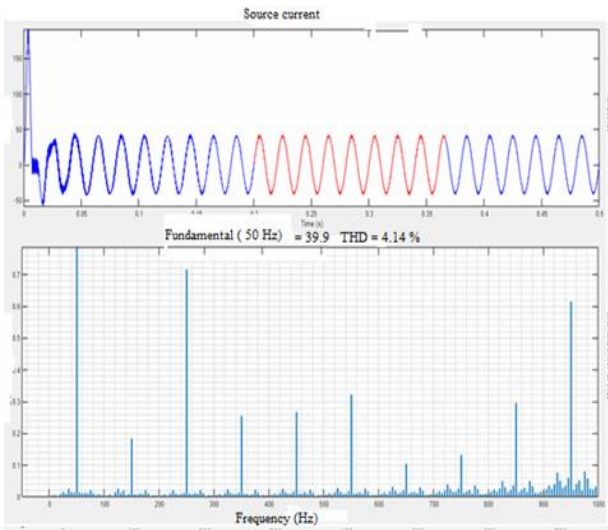

Fig. 3 MATLAB simulation results with PID method for THD Measurement

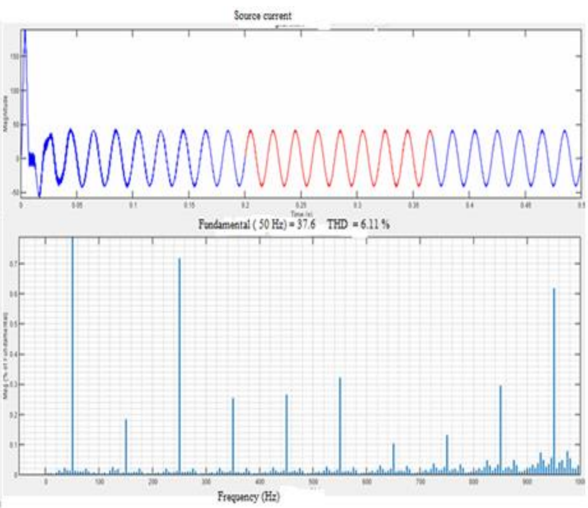

Fig. 4 MATLAB simulation Results with HYSTRESIS method for THD measurement

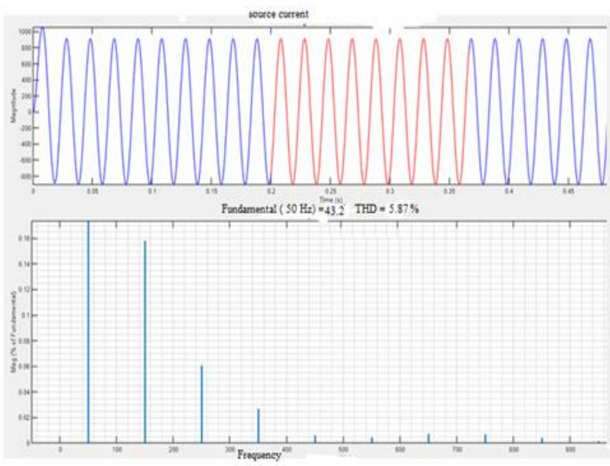

Fig. 5 MATLAB simulation Results with FUZZY method for THD Measurement

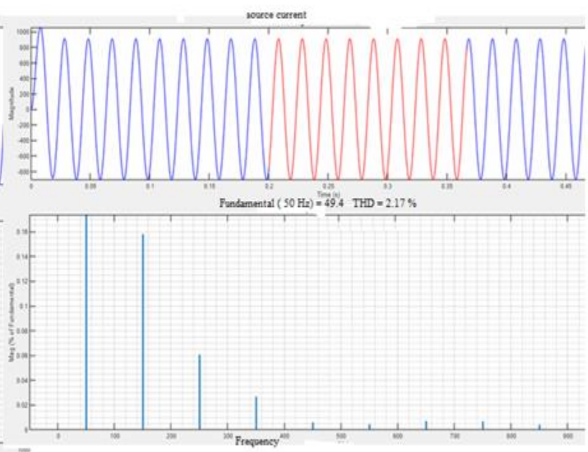

Fig. 6 MATLAB simulation Results with proposed SRF method for THD Measurement

The simulation of various switching techniques for Vienna rectifier with different load conditions has been performed and results for THD and PF have been summarized Table III.

Table III : summary of results with various load conditions for Vienna rectifier

Control theory >>	PID		HYSTRESIS		SRF (PROPOSED)	
Parameters >>	**THD**	**PF**	**THD**	**PF**	**THD**	**PF**
Load R=10 Ω	2.74	0.9642	2.96	0.8884	1.22	0.9938
Load R=10 Ω L= 1 µH	2.98	0.9610	3.04	0.8534	1.45	0.9910
Load R=100 Ω L= 10 µH	3.13	0.9610	3.87	0.8574	1.67	0.9923
Load R=10 Ω L= 100 mH	3.78	0.9615	3.90	0.8434	1.68	0.9927
Load R=100 Ω L=500 mH	3.98	0.9612	3.91	0.8494	2.02	0.9845

VI. Conclusion

The Vienna rectifier having comparative advantages like low conduction loss, switching loss, low power density compare to other three phase PFC increases interest to focus on performance improvement of it by various converters. A comparative study and analysis of three control techniques with proposed SRF control theory have been implemented for Vienna rectifier using MATLAB simulink. From summary result Table III , it can be seen that the current THD value has been decreases significantly and improved power factor has been achieved with proposed SRF control theory.

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