Design and Analysis of a Six-Phase Vienna Rectifier

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Abstract

Vienna rectifiers are used in certain industrial applications. They are generally designed as 3-phase. This study focus is design and availability of 6-phase Vienna rectifier to be used with a 6-phase generator. As the demand for electrical power increases, an increase in generator voltages is needed to increase the efficiency of the system. This brings about the implementation of an AC/DC converter with reduced disturbing input current effects. This paper proposes a 6-phase Vienna rectifier with smooth input current with a reduced THD . Control algorithm and power electronic circuit were all simulated in PLECS. Hysteresis control loop was built-in for output voltage control. Standard PI controllers were implemented for voltage control, and to balance the output filter capacitor voltages. Mathematical model explaining input and output voltage relations is presented in the paper. A naturally low THD was obtained as a contribution of 6-phase design.

1. Introduction

Since diode and thyristor rectifiers draw input currents which have high total harmonic distortion (THD) from the grid, their use should be avoided. To prevent grid disruption, some new developments or improvements of existing topologies have been performed. In references [1-3], Power Factor Correction (PFC) rectifiers have been developed by combining boost and buck converters in series or parallel with the rectifier circuits. Additionally, due to the increasing use of six-phase systems in wind systems [4-6], there is a need for six-phase rectification. In reference [7] and [8], an active six-phase PWM rectifier has been developed. However, a 6-phase Vienna rectifier has not been found in the literature. Furthermore, new control algorithms were developed in reference [9], such as the Carrier-Based (CB) PWM Method, and in reference [10], Feedforward Compensation, to achieve lower THD values, even though Vienna naturally has lower THD.

Vienna Rectifier is a single direction boost type rectifier; they cannot be operated opposite direction to invert the DC source to AC. In other words, Vienna rectifiers are a non-generative boost type rectifier [9]. They are used for different industries such as aviation, telecommunication power systems, and wind turbine systems [11-13].

Vienna rectifier's fundamentals are acceptable since output voltage is controlled by sinusoidal main current source and it has low-blocking voltage stress on power transistors [11]. Output voltage is controllable by transistors connected parallel to an uncontrolled diode in full wave rectifiers to have a kind of DC-DC boost converter.

One of the Vienna rectifiers' advantages is high efficiency, and other advantages can be listed as simple structure, power density, and high reliability [14]. Especially, high reliability in safety critic systems such as aviation and automotive is hard to overcome in new electrical systems because of complexity and using of numerous components. In other words, Vienna rectifier has less active power components than that of PWM rectifiers, which is one of the main advantages. [15]. On the other hand, Vienna rectifiers' switches exposed to half of the DC bus voltage, and that makes them appropriate for high voltage DC systems [16].

Even though Vienna rectifiers are three-level converters, the controlled point is only the neutral point connection. When there is a phase difference between the reference voltage and the input current, the converter generates voltage pulses when the reference voltage and currents have different signs, which leads to low-frequency voltage distortion in the power supply of the rectifier [17]. Therefore, the zero crossing of each phase current affects all phases, and distortion appears especially at light loads [18].

This study focuses on the design of a six-phase Vienna rectifier and analyze it. Multi-phase generators are employed more in systems because they provide sinusoidal mmf with fewer harmonics. On the other hand, polyphase generators have less torque ripples. Furthermore, power consumption for each phase is decreased [19], resulting in increased efficiency. Using 6-phase systems as generators requires the rectification of these 6 phases to DC due to the supply of DC grids [20].

As a consequence of the Vienna Rectifier system being unidirectional, it can only be used as a rectifier. Additionally, reactive power generation is limited [21]. In Section 1, brief introduction and general information in Section 2 are given. Section 3 includes Vienna rectifier design. Results are given in Section 4. It was shown that a six-phase Vienna rectifier is possible and effective.

2. General Information

Modelling any electric circuit by mathematical approach is crucial to clarify the operation states of circuits with equations. The defined equations are available to be used to develop control algorithms for a circuit.

Vienna rectifier has been defined by mostly used modelling common approaches of a circuit in literature. In [22], a star connected Vienna rectifier operating in continuous conduction mode (CCM) can be seen in **Fig.1.a**, and modelling as average of circuit is given in **Fig.1.b**. Mathematical equations can be created by considering the switching cycles, and controller can be developed.

Another modelling approach is small signal modelling of the Vienna rectifier, and in [23] digital signal processing based small signal model identification was performed, and transfer functions were obtained. The model was validated by both using the simulations and practical study.

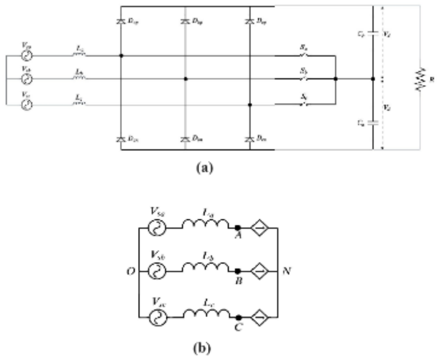


Fig. 1. a) Vienna Rectifier – Star Connected, b) Average Model of Switching

The need for two feedback loops to control operating of the Vienna rectifier makes the modelling hard [24]. In [24], three phase, four wire Vienna rectifier can be accepted as a three single phase boost power factor correction rectifier by connecting the midpoint of the capacitor to neutral. Here, the output capacitors are connected parallel to each phase. A control algorithm is developed for single phase and it is built for other phases by phase shifting.

2.1. Operation Conditions of Single-Phase Vienna Rectifier

Connecting the midpoint of the capacitor to neutral point makes the three phase, four wire, three level rectifier decoupled to three single phase rectifiers. **Fig.2.** represents the single-phase Vienna rectifier where V_s is the input voltage, L is the input inductor. Two diodes are used to create half-bridge circuit, namely, D_p and D_n. C_p and C_n are capacitors to filter output. The load has been shown as R only, resistive load. The semiconductors used in circuit are represented only as a regular switch, since only one switch can be in conduction or non-conduction mode related to the source polarity.

A single phase modeled Vienna rectifier has 4 different operation modes. The modes are combinations of Switch ON / OFF modes, and AC polarity POSITIVE / NEGATIVE stages which can be seen in **Fig. 3.**

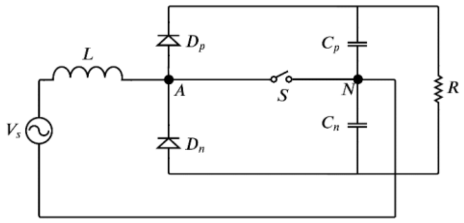


Fig. 2. Vienna Rectifier-Single Phase

Mode I

Mode I is represented in **Fig. 3.a** when AC source in positive polarity, and the switch is ON. Inductance L charges by AC source, and load R supplied through capacitors C_p and C_n. Current i_a flows from source to capacitors neutral point through switch.

Mode II

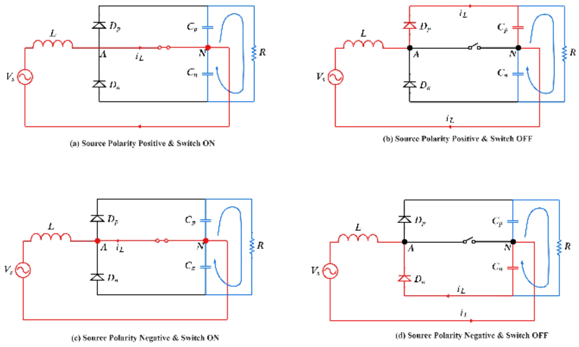
Mode II is given in **Fig.3. b.** While this mode is active, switch is OFF, and the inductor L is discharged via the capacitor C_p, and the load R is supplied by source and C_n. Current i_a flows through the capacitor C_p and diode D_p towards the neutral point.

Mode III

Mode III is seen in **Fig. 3.c** and this is the opposite equivalent of Mode I, and because of this reason, the current flows through switch towards the neutral point.

Mode IV

Mode IV is seen in **Fig. 3.d** and this is the opposite equivalent of Mode I, and because of this reason the current flows through C_n and D_n towards neutral point.



(a) Source Polarity Positive & Switch ON

(b) Source Polarity Positive & Switch OFF

(c) Source Polarity Negative & Switch ON

(d) Source Polarity Negative & Switch OFF

Fig. 3. Single Phase Vienna Rectifier Operation Modes

2.2. Average Model of Vienna Rectifier

Basically, Vienna rectifier boosts the DC voltage. When three phase is decomposed to three single phases, the circuit topology might be acceptable as DC-DC boost converter to model and create equations, because the uncontrolled rectified voltage is manipulated by connected switches through the inductor, and capacitor. The inductor and output capacitors are used as current, and voltage sources, respectively. When the AC voltage goes to zero, the switching duty-cycle is decreased and output voltage is boosted to the desired value.

The average model is created according to the operation modes, and the equations are written according to those equivalent circuits in these modes.

In Mode I, there are two individual loops and the first loop accommodates the inductance and voltage source creating the voltage equation given in (1) where L is the input inductor and r_L equivalent resistor of inductive L.

$$L\frac{di_L}{dt} = v_s - i_L \cdot r_L \tag{1}$$

The second loop accommodates the output capacitors and load resistance. By assuming the average voltage of capacitors v_{d1} and v_{d2} are the same (v_d) , (2) can be written.

$$C\frac{dv_d}{dt} = \frac{-2v_d}{R} \tag{2}$$

In Mode II , the switch is OFF, and the equivalent equations are

$$L\frac{di_L}{dt} = v_s - v_d - i_L \cdot r_L \tag{3}$$

$$C\frac{dv_d}{dt} = i_L - \frac{2v_d}{R} \tag{4}$$

In order to combine the equivalent equations, d which is the duty cycle of the switch is used representing the ON/OFF stages of the switch where d=1 and d=0 denotes the switch is ON and OFF, respectively.

If the inductor and capacitor equations are merged related to switching modes (5) and (6) can be obtained.

$$L\frac{di_L}{dt} = v_s - v_d(1-d) - i_L r \tag{5}$$

$$C\frac{dv_d}{dt} = \frac{-2v_d}{R} + i_L(1-d) \tag{6}$$

(5) and (6) can be expressed in state space form (7) to model a single-phase Vienna rectifier.

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_d \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & \frac{-(1-d)}{L} \\ \frac{(1-d)}{C} & -\frac{2}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_d \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_s \tag{7}$$

3. Vienna Rectifier Design

3.1. Inductor Design

Current ripple is affected by source polarity and control strategy. Negative polarity can cause a higher current ripple while positive one can reduce.

In (7), derivation of inductor current indicates inductor current ripple related to time which is re-written in (8).

$$\frac{di_L}{dt} = -\frac{r}{L}i_L - \frac{v_d(1-d)}{L} + \frac{v_s}{L} \tag{8}$$

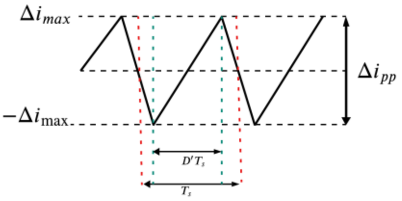


Fig. 4. Inductor Current Period

First term can be neglected, since it is a very small value. di_L represents the Δi_{pp}, and dt indicates the switching ON or OFF time. During OFF time, d is zero and (9) can be written as

$$\frac{\Delta i_{pp}}{D'\,T_s} = -\frac{v_d}{L} + \frac{v_s}{L} \tag{9}$$

where T_s is switching period and D' is (1-DutyCycle) of switch. Inductor value can be calculated as in (10).

$$L = \frac{D'\,T_s(-v_d+v_s)}{\Delta i_{pp}} \tag{10}$$

3.2. Six Phase Vienna Rectifier Model

High power demand in different applications such as marine [25], wind turbines [26], and aviation [20] cause heading towards six-phase generators to reduce the current for each phase in generator. Here in this section, a six-phase Vienna rectifier design is presented. The rated output voltage and power values of the design are 800 V and 21 kW. The proposed design simulation was simulated PLECS as seen in **Fig. 5.**

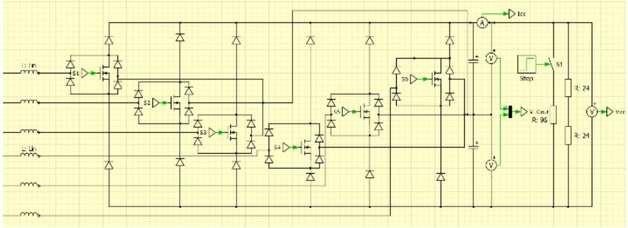


Fig. 5. Six Phase Vienna Rectifier

Six-phase source was created by merging two different three phase source while applying a phase shift. Ideal switches are used.

Closed loop control was applied and Hysteresis control was implemented as can be seen in **Fig. 6** including voltage loop, inner current loop and center point voltage controller for DC filter capacitances. Hysteresis loop caused simplicity for implementations, but switching frequency varies, and hysteresis control does not guarantee keeping the ripple in limited arrange while it is implemented by digital controllers [27].

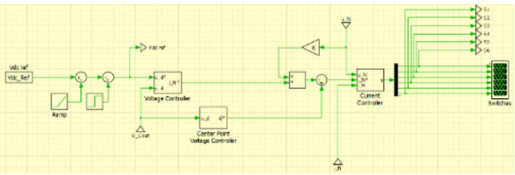


Fig. 6. Hysteresis Control Loop

For error compensation, continuous PID controllers were used as seen in **Fig.7** and **Fig.8** for voltage and center point voltage controller.

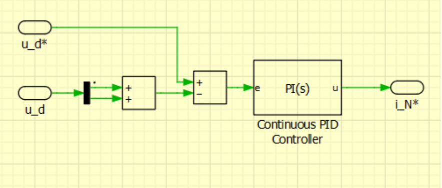


Fig. 7. Voltage Controller

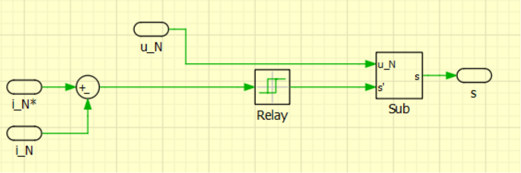


Fig. 8. Current Controller

Fig 8. shows the Hysteresis controller. The relay sets and resets according to the determined positive and negative limits of the current, and this helps to keep the inductor current ripple or current error at a low value.

4. Simulation Results

Four different scenarios in one simulation period were applied. The ability of the control method to follow the reference voltage while the load also changes according to the scenario was analyzed and THD was also calculated. All intervals and events are marked and zoomed versions of signal changes are also inserted on **Fig. 9.** The 1st event began with the application of 800 V reference voltage and the rectifier was loaded with 13 kW constant load (constant current as 16.25 A). Then the reference voltage was shifted to 825 V during the 2nd interval and the load was increased to 14 kW (the load current was linearly increasing up-to 17 A). As the reference voltage was being kept constant (so was the current), the load was increased to 21 kW and 25,45 A at 0.5 second at the 3rd point. Then at 4, the load power and the current were reduced to 16 kW and 22,1 A, respectively, at 725 V reference voltage.

The change in reference and output voltages and instantaneous tracking ability can be seen in **Fig. 9.** Change in load current is given in **Fig. 10**. The response to an instantaneous increase in load current (the 3rd point) can be seen in **Fig. 11**. The total voltage drop was compensated in 47.5 milli seconds.

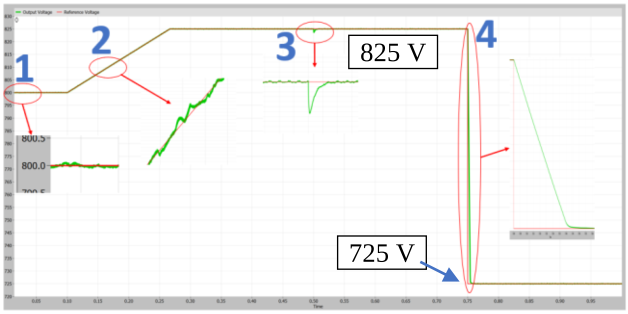


Fig. 9. Reference (red) and Output (green) Voltages

The one phase of the input currents of the scenarios were as seen in **Fig.12**, and scenarios are marked as **Fig. 9.** Input current has same behavior as output current and RMS values of the currents for regions were written in **Fig.12**. Second scenario voltage reference increasing causes also increasing of the input current and its marked in **Fig 12** by red line. The frequency of the input currents was equal to that of the source. Further, the THD of the current for the given power changes are 9.5%, 9%, 6%, and 7.5%, respectively. It was seen that a low harmonic distortion was obtained at the input side, although no special attention was paid for a lower THD. The reason for the low THD comes from the nature of 6-phase Vienna rectifier design. Table 2 shows the THD results for developed algorithm to have less THD in [9], and [10], and used algorithm in this study.

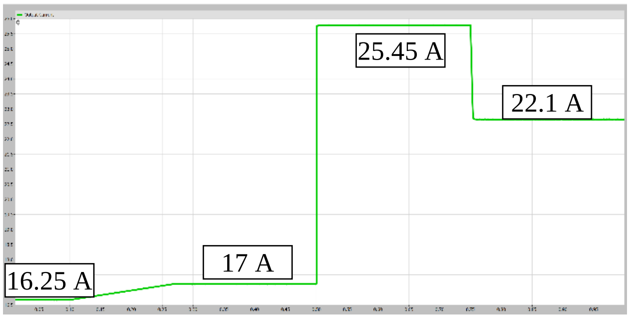


Fig. 10. Output Current

All of the scenarios' results are seen in Table 1.

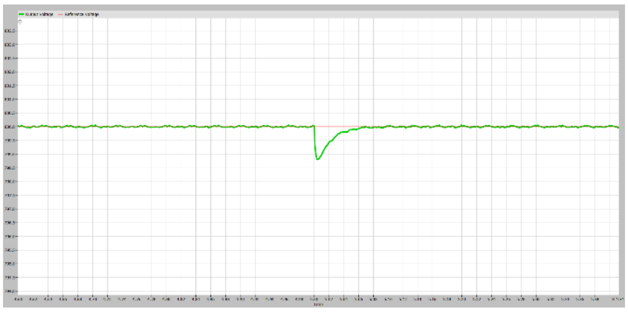


Fig. 11. Load Change Effect in Output Voltage

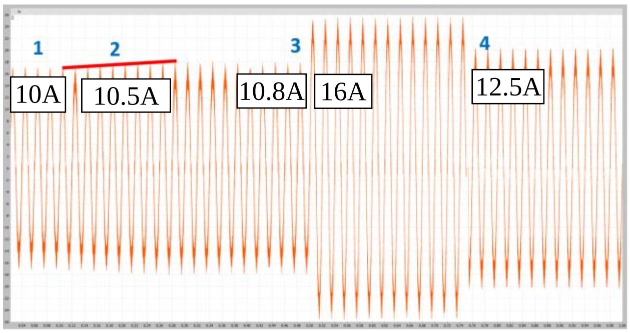


Fig. 12. AC Input Current

Table 1. Simulation Scenarios and Results

Scenarios	Input RMS Voltage(V)	Output Voltage (V)	THD (%)	Output Power(kW)
I	220	800	9.5	13
II	220	825	9	14
III	220	825	6	21
IV	220	725	7.5	16

Table 2. THD Comparison

	CB PWM Method	Feedforward Compensation	Hysteresis Control
THD (%)	3.5	<1	6

5. Conclusion

In this study, a 6-phase Vienna rectifier was designed and analyzed by means of simulations. Whole mathematical system model was also given to introduce the relation between input and output voltage. Hysteresis control was applied, and standard PI controllers were implemented for voltage control, and to balance the output filter capacitor voltages. Several loading scenarios were applied, and it was seen that output voltage can follow the reference voltage and the voltage output could be kept at the desired value after load changes. Moreover, for all loads, it was shown that a naturally low THD coming from 6-phase supply was obtained, although no attention in the control loop was paid for reducing it.

6. References

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