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Sliding mode control of Vienna rectifier with output voltage control

[1]Rouzbeh Reza Ahrabi, [2]Mehdi Elmi, [3]Mohammad Reza Banaei
Department of Electrical Engineering, AzarbaijanShahidMadaniUniversity, Tabriz, Iran

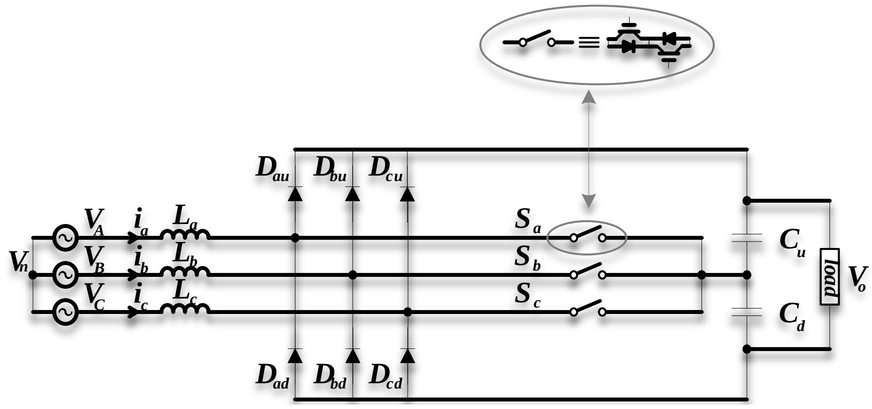
Abstract: In this paper, a Vienna type boost rectifier is discussed and controlled using sliding mode control. Sliding mode control function is defined to control output. The object of this system is to provide desired output DC voltage in any possible circumstances.

Introduction:

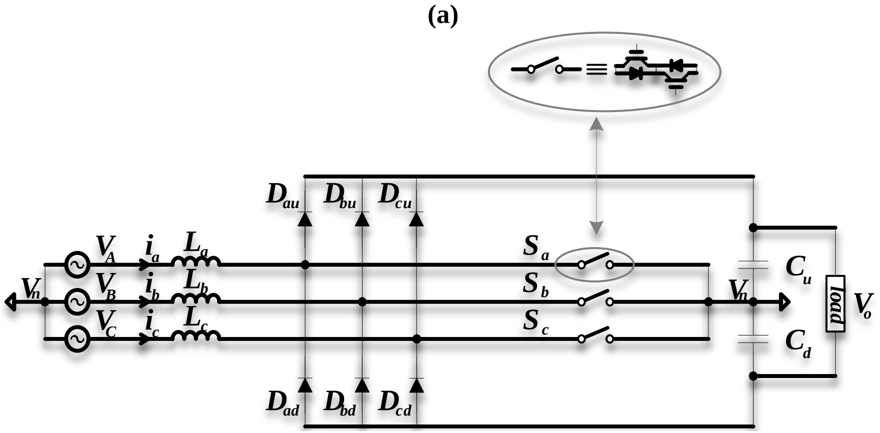
Three-phase AC-DC power supplies (rectifiers) are widely used in many aspects of power systems, such as: 1) High-voltage direct current (HVDC) systems; 2) Uninterruptible power supply (UPS); 3) Variable speed drives; 4) As generator side converter for permanent-magnet synchronous generator (PMSG) [1]. Conventional rectifiers are known using diodes and thyristors to supply uncontrollable and controllable dc power. Current harmonics are the most important problem of these converters, which causes lower power quality, and voltage distortion. Another problem is the low power factor at input side of rectifiers. Several standards are issued to prevent or decrease the mentioned problem such as IEEE-519, IEC555. In order to overcome the problems some options were used, such as passive filters, active filters and hybrid filters. However, these options increase the cost and losses of system which are good reasons to reduce efficiency of the converter [2]. Because of these problems, AC-DC converters can be improved, using power switches and changing in the circuit diagram [3-8], [2].Various AC-DC converters in terms of control system and circuit structure have been introduced up to now [2], [9-11]. In [2] AC-DC converters are divided into five major groups Buck, Boost, Buck-Boost, Multilevel and Multi-pulse. Each one of these converters can operate in unidirectional and bidirectional and in particular goals with particular benefits. In [9] rectifiers are divided into two major groups; controlled and uncontrolled rectifiers that each one of them is divided into isolated and non-isolated and at last each group appear in bridge and full-wave. Power factor correction (PFC) of conventional rectifiers and passive diode rectifiers and performance of the three phase buck type rectifier with PFC are studied in [10-11]. In addition, the essence of four active three-phase PFC rectifiers (active six-switch boost-type PFC rectifier, the VIENNA rectifier, the active six-switch buck-type PFC rectifier, and the SWISS Rectifier) are dedicated. Each one of these rectifiers has positive and negative points in various applications. For example, the diode rectifiers with a boost converter could regulate the output voltage and also improve the input power factor. If the input three-phase voltages are unbalance, correcting the power factor may be one of problems. If the load is sensitive to voltage changes, so the adjustment and balancing of rectifier's output voltage with poor control capability will problematic under distortion and harmonic condition of utility side. Three-phase Vienna rectifier [7] with six diodes and three bidirectional power switches is one of acceptable structures in PFC and boosting voltage, which is widely discussed in recently published papers with promoting control policies [1], [12-17].One of the most important benefit of Vienna rectifier is its capability to work under various distortions in input side such as harmonic distortion and unbalance input voltages [18-19]. The introduced structures in [18-19] are three-phase three wires which need to complicated control system under unbalance input voltage conditions. In [20] to avoid from mentioned complication the Vienna rectifier for three-phase four wires system is proposed. The benefit of fourth wire appears in unbalance and distorted input voltage to lead distortions into neutral point. Many control methods have been introduced to control Vienna rectifier [4], [9] and [21]. These techniques are effective to control Vienna rectifier in PFC and output voltage regulating. But it should be noted that under distorted input voltage conditions control of the system is complicated. Sliding mode control (SMC) is one the methods, which widely have been used in power electronic converters [22-28]. SM is an effective control method with high frequency performance for nonlinear systems. It has some advantages such as simple implementation, disturbance rejection, strong robustness, and fast responses, but the controlled state may exhibit undesired chattering [29]. In this paper, sliding mode is used to control the three-phase four wires Vienna rectifier under normal and distorted conditions of input voltage. Each phase of three-phase input is controlled individually in order to make control easier and clear. In order to prevent chattering phenomena the fixed frequency SMC is utilized.

System configuration

Three-phase three wires and four wires Vienna rectifiers are illustrated in Fig. 1(a) and Fig. 1(b) respectively. In this paper three-phase four wires Vienna rectifier is considered. In the normal condition V_A, V_B and V_C are input three-phase voltage and each phase has 120° phase shift in comparison to other phases. L_a, L_b and L_c are input filter inductors. S_a, S_b and S_c are bidirectional power switches, insulated-gate bipolar transistor (IGBT) with common emitter connection for each double switches.



(a)



(b)

Fig. 1
a. Three-phase Vienna rectifier
b. Three-phase Vienna rectifier with connected fourth wire

Based on the presented structure in Fig. 1(b) the three phase system can be considered as 3 single phase system without loss of generality and exclusive feature of rectifier. Fig. 2 show single-phase structure of Vienna rectifier. Compensation scheme and control procedure will be executed on single-phase structure then it will be generalized to three-phase system.

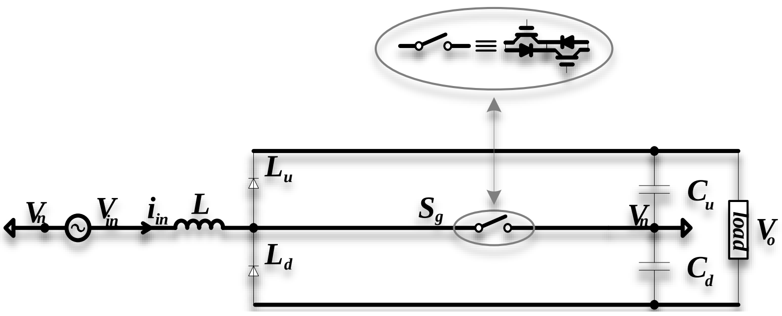


Fig. 2 Single-phase Vienna rectifier

Converter performance

Vienna rectifier perform as boost AC-DC converter. In order to describe performance of the Vienna rectifier, single-phase structure of AC-DC converter is considered as Fig. 2. Performance of the Vienna rectifier is divided into two states which are shoot through and non-shoot through.

Shoot through

In this state without noticing to input voltage phase, power switch $S_g$is turned on and AC current flows through inductor L, power switch S_g and input voltage source. Fig. 3(a) shows shoot through state of Vienna rectifier, which bidirectional power switch is turned on and diodes L_u and L_d are reverse biased.

Non-shoot through

In this state power switch$S_g$is turned off and diodes L_u and $L_d$are forward biased due to inductor current. Fig. 3(b) shows currents path in the non-shoot through.

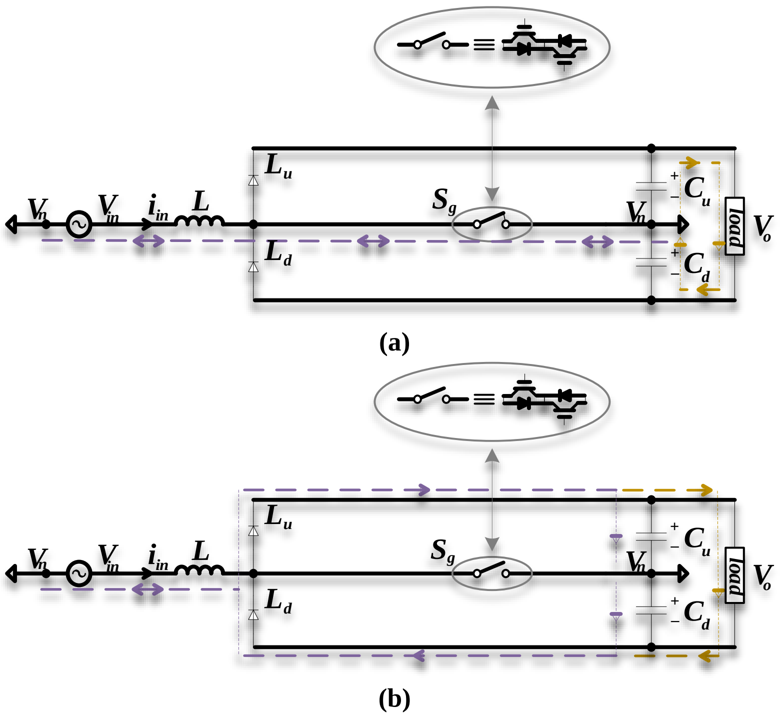


Fig. 3
a. Single-phase Vienna rectifier in shoot-through state
b. Single-phase Vienna rectifier in non-shoot-through state

Control scheme

Control scheme is presented in order to combine with sliding mode control. Reference voltage is used by SMC to balance the capacitor's voltage.

Sliding mode control:

Fig. 4 shows performance diagram of control system, which will merge with sliding mode in order to control the Vienna rectifier.

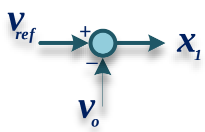


Fig. 4 Diagram of control system

The sliding surface, S,is defined as:

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 \tag{4}$$

That α_1, α_2 and α_3 are the sliding surfaceindexes. The logic state of power switch $S_g$is defined as follows:

$$u = \frac{1}{2}(1+\text{sign(S)}) \tag{5}$$

where, u is switching function. In order to control Vienna rectifier with PFC and output voltage balancing capabilities, the input current error x_1, the output voltage error x_2 and the integral of the voltage and current errors x_3 are considered as control variables which are expressed as:

$$i_{ref} = K\left[v_{ref} - v_o\right] = K\left[v_{ref} - v_o\right] \tag{6}$$

$$\begin{cases} x_1 = i_{ref} - i_L \\ x_2 = v_{ref} - v_o \\ x_3 = \int\left[x_1 + x_2\right]dt \end{cases} \tag{7}$$

K is the gain of the voltage error. A large value for K is chosen to improve dynamic response and to minimize the steady state voltage errors [30]. Dynamic model of Vienna rectifier based on Fig. 2 can be obtained as follows:

$$\begin{cases} \dot{x}_1 = \dfrac{d\left(i_{ref} - i_L\right)}{dt} = K\left[-\dfrac{dv_o}{dt}\right] - \dfrac{v_i - \bar{u}v_o}{L} \\ \dot{x}_2 = \dfrac{d\left(v_{ref} - v_o\right)}{dt} = -\dfrac{dv_o}{dt} \\ \dot{x}_3 = x_1 + x_2 = K\left[v_{ref} - v_o\right] - i_L + v_{ref} - v_o \end{cases} \tag{8}$$

$\bar{u} = 1 - u$ is considered to be complementary logic of u. v_i and v_o are instantaneous input and output voltages. L donates inductor of the converter. The equivalent control signal of the SM current controller when applied to the Vienna rectifier is obtained by solving (9).

$$\frac{dS}{dt} = \alpha_1 \dot{x}_1 + \alpha_2 \dot{x}_2 + \alpha_3 \dot{x}_3 = 0 \tag{9}$$

which gives

$$uv_o = \left[v_{ref} - v_o\right]\left[L\frac{\alpha_3}{\alpha_1}K + L\frac{\alpha_3}{\alpha_1}\right] - \frac{dv_o}{dt}\left[LK + \frac{\alpha_2}{\alpha_1}\right] - \frac{\alpha_3}{\alpha_1}Li_L + v_o - v_i \tag{10}$$

where,

$$K_1 = L\frac{\alpha_3}{\alpha_1}K + L\frac{\alpha_3}{\alpha_1} \tag{11}$$

$$K_2 = LK + \frac{\alpha_2}{\alpha_1} \tag{12}$$

$$K_3 = \frac{\alpha_3}{\alpha_1}L \tag{13}$$

Considering $v_{ramp}= uv_o$ and replacing uv_owithv_r then we have

$$v_r = K_1\left[v_{ref} - v_o\right] - K_2\frac{dv_o}{dt} - K_3 i_L + v_o - v_i \tag{14}$$

$$v_{ramp} = uv_o \tag{15}$$

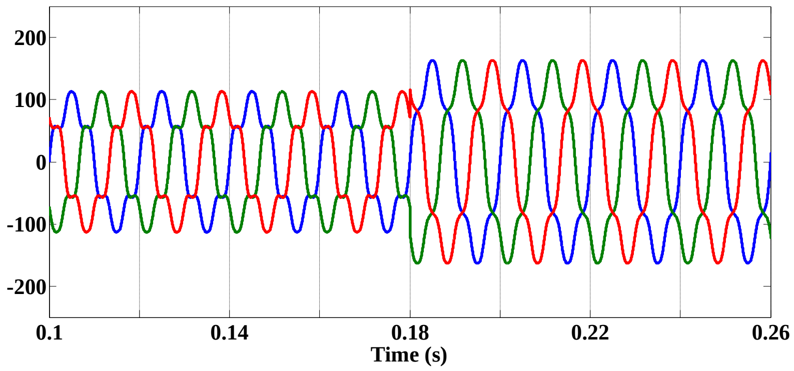
Because of fixed-frequency structure of presented SM controller, the chattering phenomenon, which is the important drawbacks of nonlinear controllers, will be eliminated.

Simulation result

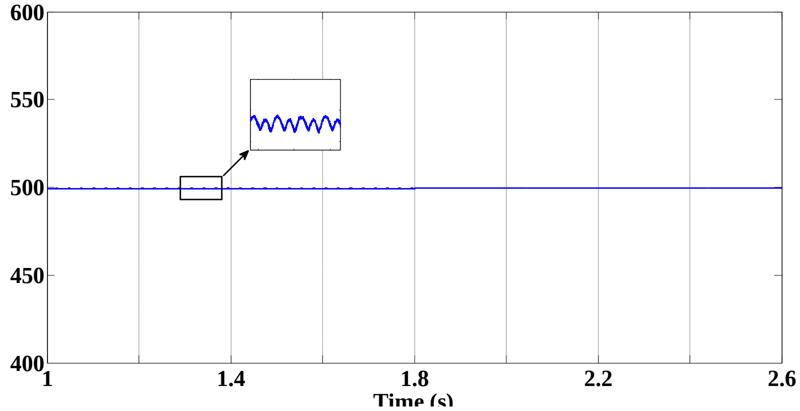
In order to verify performance of the proposed SMC on three-phase Vienna rectifier Matlab/Simulink is done. Simulations is operated in discrete mode with 1 µs step size. Parameters of Vienna rectifier are listed in Table I. *k*, orthogonal systems bandwidth factor is 0.3. In this case the input signal consist of main harmonic with 20% fifth harmonic, 5% seventh harmonic and 2% eleventh harmonic with 20.71% total harmonic distortion (THD). Main harmonic appear with peak voltage of 100 (V) and the frequency is 50 (Hz). Fig. 5(a) shows the distorted utility side voltage which supplies a Vienna rectifier and at 0.18 sec its fundamental component is increased up to 50%. The output DC voltage of Vienna rectifier is shown in Fig. 5(b). It can be seen from this figure that the output voltage remains constant in its reference value (500v) despite of input voltages changing.

Table I Tested system parameters

R_{Load}	150 (Ω)
L	1 (mH)
$V_{i(peak)}$	100 (V)



(a)



(c)

Fig. 8 Simulation results for three-phase grid connected Vienna rectifier with distorted input voltage (Fundamental voltages are increased 50% at t = 0.18 s)
a. Grid side voltage
b. Output DC voltage

These results verify the proper performance of presented control system based on combination of SMC and orthogonal systems.

Conclusion

Sliding mode control is applied to Vienna rectifier. Output voltage is controlled and stabilized in desire voltage. Despite of input distortions,output DC voltage is stabled on desire voltage that guarantee the performance of control system.

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