

An Improved Control Strategy for Full-controlled Single-phase H Bridge Rectifier

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Abstract. In this paper, an improved single-phase H bridge rectifier controller with high power factor, and low DC ripple is presented. After introduction the working principle and electrical circuit topology of single-phase rectifier with the H bridge, the design method of its essential parts of controller, phase locked loop (PLL) and proportional resonant (PR) control strategy, is discussed. These two parts play important role to achieve extremely high power factor and low DC ripple. And via Matlab/Simulink simulation, this conclusion is showed. At the last part of this paper, the physical experiment was carried out on a 10kV rectifier and the result proved the effectiveness of the presented controller.

Introduction

Direct current (DC) devices are widely used in our daily life and industrial applications. But until now, the already used power grid only supplies electrical energy in the form of alternative current (AC). Thus rectifiers which have the function to convert AC power to DC power are becoming an essential link between the AC power grid and DC energy consuming devices. There are many ways to realize this conversion. Maybe the simplest one is non-controlled rectifier bridge which is just directly constituted by several electrical diodes [1]. Although DC power is supplied but its power factor and power quality seems too low to satisfy the electrical energy integration requirements of power grid [2]. Although some effective solutions were proposed, just like PFC in [3], but generally speaking full-controlled rectifiers perform much better on the aspects of a higher power factor and less DC ripple. At the same time, with advanced digital controller technology, it's also easier to regulate flexibly magnitude of the DC voltage with a fast speed. This benefits the operation of DC energy consuming devices. But it's a pity that most current researches focus on the three-phase situations and less attentions is paid on single-phase rectifier [4].

In this paper, an improved controller for single-phase rectifier was presented. Firstly the typical topology of single-phase rectifier is introduced. Then the PLL and PR control strategy are discussed. Thirdly with simulation method, the proposed method is proved by Simulink. The last part of this paper, a physical experiment of 10kW rectifier is showed and effectiveness of control strategy is proved.

Full-controlled Single-phase H Bridge Rectifier

The typical topology of full-controlled single-phase H bridge rectifier is shown in Fig.1. L_s is inductance on the AC input side and is used to filter out harmonics and store energy temporarily. R_s is impedance of the filter inductor. S_i ($i = 1,2,3,4$) represent IGBT and VD_i ($i = 1,2,3,4$) mean parallel connected freewheeling diodes. Filter capacitor C at the output side will benefit to reduce voltage ripple and accelerate transient process. Load Z connected after the C .

It should be noted that this full-controlled single-phase bridge rectifier works in a way just the

same as a BOOST circuit. S_i alternately turn on and off, thus the energy stored in inductor is discharged and then charged again. Thereby the output voltage is pumped times higher than u_s [5].

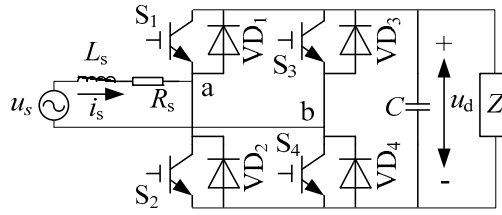


Fig.1. The typical topology of single-phase H bridge rectifier

Phase Locked Loop

In order to make the phase of input AC current absolutely keep the same as the AC voltage, which means high power factor obtained, the high precision phase measurement method is very important. One method is called phase locked loop (PLL) which widely used in three-phase system. Assuming that there lie three-phase symmetrical signals, and phase angle difference between each other is $\pm 2\pi/3$ and phase u_a is taken as the reference, thus three signals are expressed as follows:

$$u_a = U_m \cos \omega t; \quad u_b = U_m \cos \left(\omega t - \frac{2}{3} \pi \right); \quad u_c = U_m \cos \left(\omega t + \frac{2}{3} \pi \right) \quad (1)$$

Through dq transformation, the three phase voltage u_a, u_b and u_c could be converted to u_d and u_q , which are the d -axis component and q -axis component respectively. This can be explained by formula:

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = \mathbf{M} \times \begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} = \mathbf{M}_1 * \mathbf{M}_2 * \begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} = \begin{pmatrix} \cos \theta^* & \sin \theta^* \\ \sin \theta^* & \cos \theta^* \end{pmatrix} * \frac{2}{3} \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{pmatrix} * \begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} \quad (2)$$

\mathbf{M} represents the matrix used to transform and θ^* is the output angle of PLL. Make $\theta = \omega t$ can obtain the following results:

$$u_d = U_m \cos(\theta - \theta^*); \quad u_q = U_m \sin(\theta - \theta^*) \quad (3)$$

From the above equation can be seen that when the phase is completely locked, ie when $\theta^* = \theta$, then $u_d = U_m$ and $u_q = 0$. The PLL controller can be designed as Fig.2 shows. The core idea is to control the u_q value equals to 0 and then the output angle θ^* is the phase of u_a, u_b, u_c .

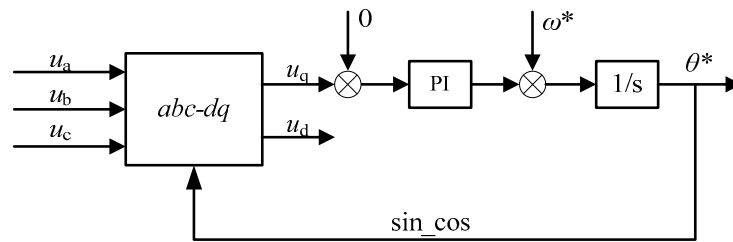


Fig.2. PLL for three-phase

But for single-phase rectifier, it fails to use above PLL to track the voltage phase because there only one phase input signal. In [6], a method is proposed via constructing two virtual orthogonal signals and then using the matrix \mathbf{M}_1 to calculate u_d and u_q . However orthogonal transformation method would filter out the information beyond 314rad/s (if the fundamental angular velocity is 314rad/s). Therefore, when the input voltage has serious harmonic pollution, then the power factor would not be very high. Actually if construct symmetrical three-phase signals by shifting the phase of the original signal (similar to the relation between u_a, u_b and u_c), the controller mentioned above is still valid. And in this way, the information of harmonic voltage is remained.

Proportional Resonant Controller

Proportional resonant (PR) controller has better performance than PI controller when tracking a AC signal. Typical PR controller transfer function is:

$$G_c(s) = K_p + \frac{2K_R s}{s^2 + \omega^2} \quad (4)$$

Where K_p is the proportional coefficient; K_R is the resonant coefficient; ω represents the resonance angular frequency which is equal to the angular frequency of the controlled variable. Taking $K_p=1$, $K_R=25$, $\omega=314\text{rad/s}$, the Bode diagram of the typical PR controller is drawn in Fig.3 (a). However, it's not easy to make the typical PR controller stable because of its seriously narrow bandwidth in nature. In order to alleviate this limitation, a revised PR controller is shown as [7]:

$$G_c(s) = K_p + \frac{2K_R \omega_c s}{s^2 + 2\omega_c s + \omega^2} \quad (5)$$

Taking $\omega_c=10\text{rad/s}$ and other parameters keeping unchanged, the Bode diagram of equation (5) is shown in Fig. 3. Compare Fig.3 (a) and (b), and find that at resonant frequency $\omega=314\text{rad/s}$ they both achieves its maximum gain, but nearby the resonant frequency, the magnitude gain of the revised PR controller performs less sensitive than the former. This will benefit its operating stably.

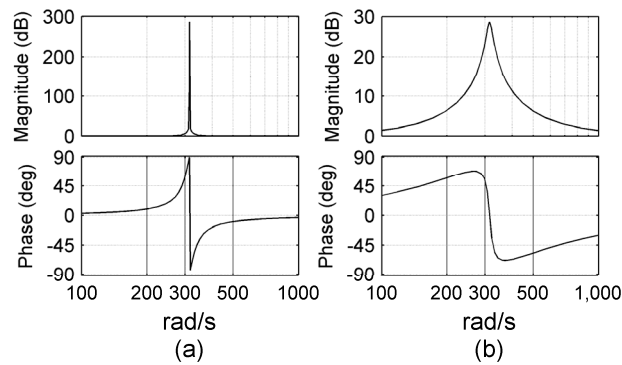


Fig.3. The Bode diagram of the typical PR controller and revised PR controller

Control Strategy

The Fig.4 is a control framework of a single-phase rectifier. The controller mainly consists of three parts: the PI controller which is used to control the DC voltage, the PR controller which is used to control power factor, the PLL which is to track the phase of the input voltage.

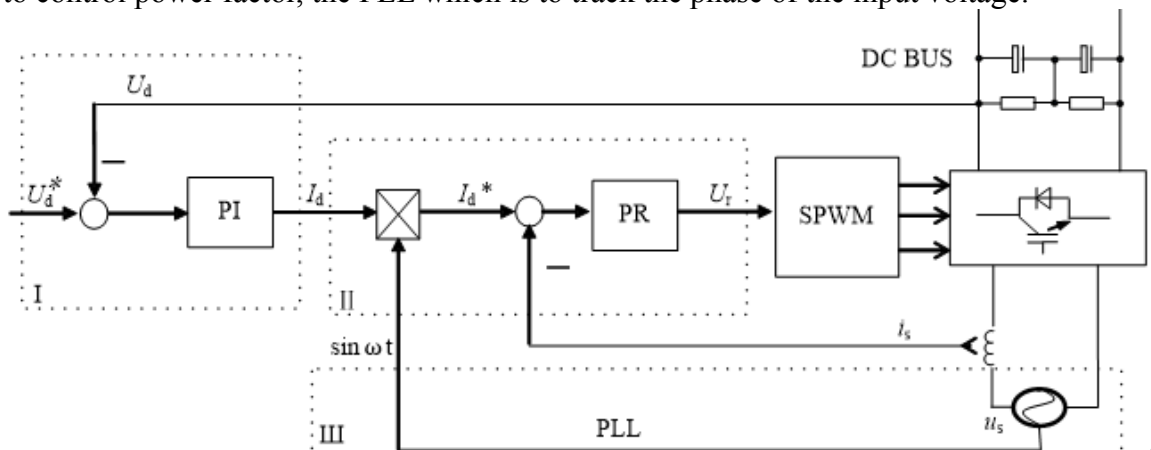


Fig.4. Control strategy of single-phase rectifier

U_d^* is reference of the DC voltage and U_d is its corresponding real-time measured value. I_d^* is reference signal of input AC current and i_s is its real-time measured value. I_d is the amplitude of I_d^* and the phase of I_d^* could be supplied by PLL. After PR controller filtering and amplifying function,

the difference between I_d^* and I_d generates the modulate wave U_r which is used to control switching of IGBT and realize the energy conversion.

Simulation results

In order to prove effectiveness of the above control strategy, build simulation model in MATLAB with respect to Fig.1. Make $L_s=5\text{mH}$ [8], $R_s=0.1\Omega$, $C=3300\mu\text{F}$, $U_d=700\text{V}$ and Z is a 49 ohms, which is a pure resistor. The simulation results are as follows:

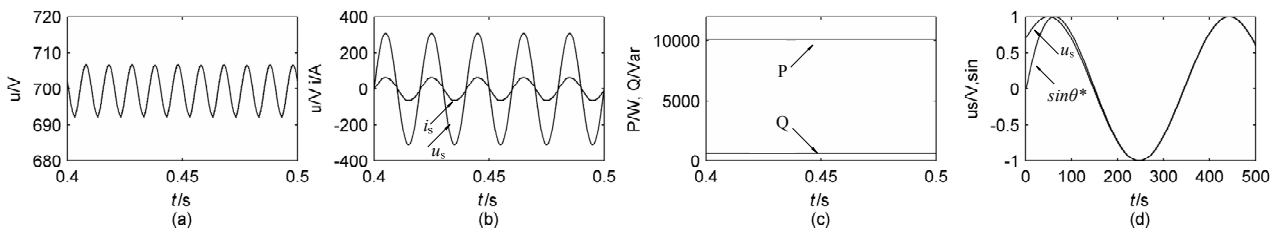


Fig.5. The simulation results

When the system state became stable, the voltage of the DC side stabilized at around 700V and the voltage ripple was about 15V as Fig.5(a) show. On the AC side, the phase of the current and voltage is the same absolutely. Hence the power factor is enough high (as Fig.5(b) show). From Fig.5(c), similar conclusion was made because active power was nearly about 10kW and the reactive power was close to 0 var. So in this way, design object to obtain high power factor and less DC ripple is realized.

Fig.5(d) is used to prove tracking phase ability of the PLL. Frequency of input AC signal is 50Hz with 45 degree initial phase. It's can be seen that within 0.01 seconds, the curve of the PLL output is successfully overlapped the input signal. This proves the PLL mentioned in Fig.2 has satisfied tracking speed and accuracy.

Experimental results

A 10kW prototype was made using the DSP TMS320F28335 which is widely used in electronic control. The control program running inside the DSP chip was written according to the Fig.4. The hardware is designed referring to the Fig.1.

The Fig.6(a) shows that after the initial oscillation and ramp increase (manually adjust to avoid the voltage and power overshoot), the DC voltage stabilizes eventually at 700V. As Fig.6(b) show, voltage ripple of the DC bus is about 5V when supplies power to a 10kW load. On the AC side the waveform of current and voltage is nearly overlapped as Fig.6(c) shows. The power factor is about 97.5%.

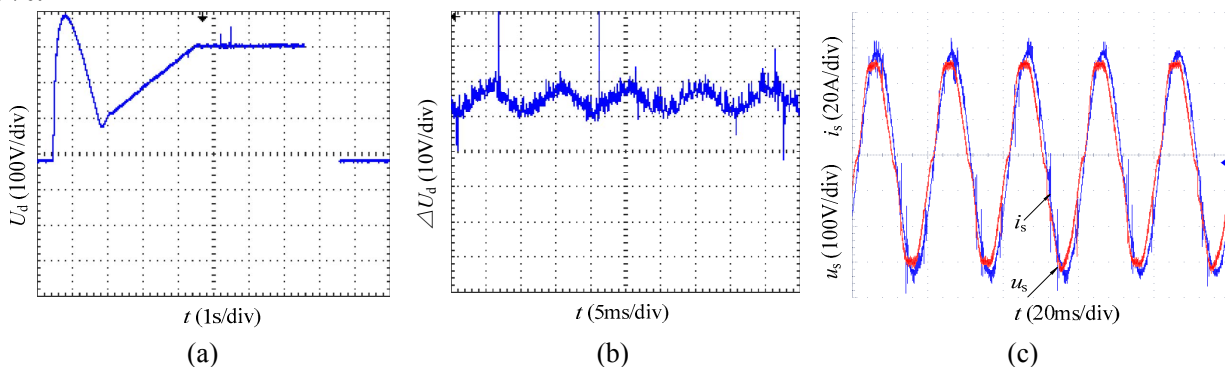


Fig.6. The experimental results

Conclusion

This paper discussed an improved design method of full-controlled single-phase H bridge rectifier with high power factor and less DC ripple. PLL and PR controller plays extremely important roles in rectifier operating. Simulation results with MATLAB and physical experiment proved the effectiveness of proposed method.

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