# CONTROL CHARACTERISTICS OF SINGLE-SWITCH, THREE-PHASE BUCK RECTIFIERS

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**ABSTRACT** - A pulse frequency modulation control method for single-switch three-phase buck rectifiers is comprehensively studied in this paper. The proposed pulse frequency control method leads the three-phase buck rectifier to a high performance system that can draw the nearly sinusoidal input-line currents. The simulated and experimental results demonstrate that the system provides low total harmonic distortion of the input-line currents, high-power factor, and good output voltage regulation.

## 1. INTRODUCTION

In recent days, a new family of single-switch three-phase multi-resonant buck-type rectifiers has been introduced.[1-3] In this circuit, the switch operates with zero-current switching and the diodes operate with zero-voltage switching. It is noted that this system draws a nearly sinusoidal current in the three-phase system. Fig.1 shows the basic circuit of the system, which is a buck-type converter of which the output voltage is lower than the input voltage. It is assumed that the typical waveforms are to be the same thing as shown in Fig.2. The rectifiers have a wide load range and low stresses on the switching devices of the DC/DC converters connected to the following stage.[1-3] It is reported that the total harmonic distortion of the system is below 5% under all the load range and its efficiency is relatively high.[1, 2]

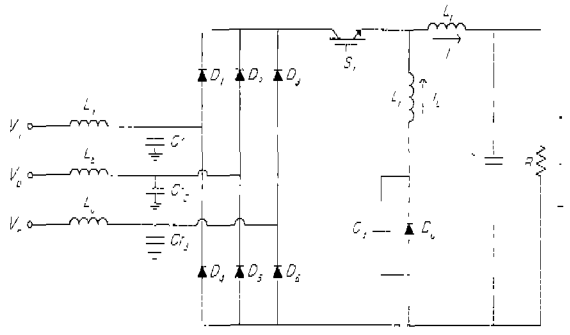


Fig.1. The basic circuit of the single-switch three-phase buck rectifier

In the point of view of control, the system needs a pulse frequency modulation method for the output voltage regulation. Pulse frequency control method can rarely be found in the literatures available. It is also said that pulse frequency control method for the single-switch three-phase buck rectifiers has not been reported in detail. A comprehensive analysis and design of frequency control method is therefore one of the main purposes of this paper.

In this paper, a set of exact modeling equations is arranged and open loop characteristics of the system are described. A control scheme considering the resulted open loop characteristics is proposed and some considerations on experiments are discussed, and finally simulation and experimental results are shown to illustrate validity of the control method.

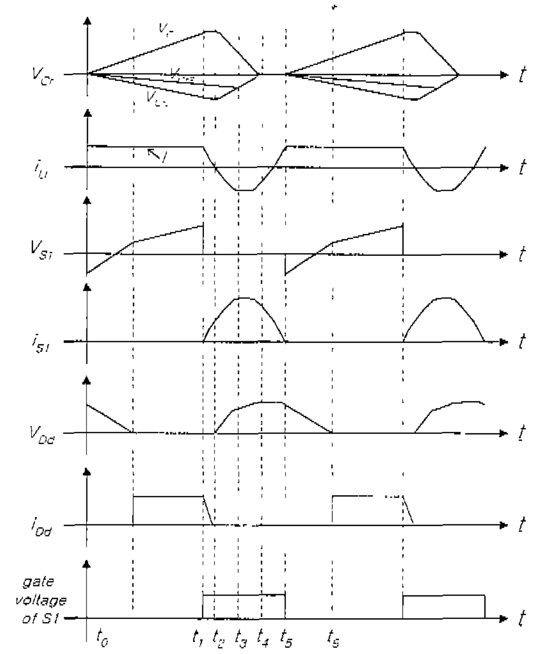


Fig.2. Typical waveforms of the single-switch three-phase buck rectifiers

## 2. CIRCUIT DESCRIPTION

The basic operating modes and associated dynamic equations of the single-switch three-phase buck rectifiers are described in brief in this section.

Mode1 ($t_0 \le t < t_1$); All switch are off except $D_d$ until the switch $S_1$ is turned on.

$$\frac{di_{L_a}}{dt} = \frac{1}{L_a}\left(V_a - v_{Cr_1}\right); \frac{di_{L_b}}{dt} = \frac{1}{L_b}\left(V_b - v_{Cr_2}\right);$$

$$\frac{di_{L_c}}{dt} = \frac{1}{L_c}\left(V_c - v_{Cr_3}\right) \tag{1}$$

$$\frac{dv_{Cr_1}}{dt} = \frac{1}{Cr_1} i_{L_a} ; \frac{dv_{Cr_2}}{dt} = \frac{1}{Cr_2} i_{L_b} ; \frac{dv_{Cr_3}}{dt} = \frac{1}{Cr_3} i_{L_c} \tag{2}$$

$$\frac{di_{L_f}}{dt} = \frac{v_{C_f}}{L_f + L_r} ; \frac{di_{L_r}}{dt} = \frac{v_{C_f}}{L_f + L_r} \tag{3}$$

$$\frac{dv_{C_d}}{dt} = 0 ; \frac{dv_{C_f}}{dt} = \frac{1}{C_f}\left(i_{L_f} - \frac{v_{C_f}}{R}\right) \tag{4}$$

Mode2 ($t_1 \le t < t_2$) ; $D_p$, $D_q$, $D_d$, and $S_1$ are on until $V_r$ is equal to $V_p$, or $V_q$, in which subscript $p$ means the greatest voltage among $v_{Cr_1}$, $v_{Cr_2}$, and $v_{Cr_3}$, and subscript $q$ means the lowest one, and subscript $r$ means the intermediate, respectively. It is noted that the following equations, which are different from those of the corresponding system variables in mode 1, can be derived according to the changed operation modes. The equations related with the rest system variables remain in the same.

$$\text{if } v_{Cr_1} = V_p, \frac{dv_{Cr_1}}{dt} = \frac{1}{Cr_1}\left(i_{L_a} + i_{L_r} - i_{L_f}\right);$$

$$\text{if } v_{Cr_1} = V_q, \frac{dv_{Cr_1}}{dt} = \frac{1}{Cr_1}\left(i_{L_a} + i_{L_f} - i_{L_r}\right);$$

$$\text{if } v_{Cr_1} = V_r, \frac{dv_{Cr_1}}{dt} = \frac{1}{Cr_1} i_{L_a} \tag{5}$$

$$\text{if } v_{Cr_2} = V_p, \frac{dv_{Cr_2}}{dt} = \frac{1}{Cr_2}\left(i_{L_b} + i_{L_r} - i_{L_f}\right);$$

$$\text{if } v_{Cr_2} = V_q, \frac{dv_{Cr_2}}{dt} = \frac{1}{Cr_2}\left(i_{L_b} + i_{L_f} - i_{L_r}\right);$$

$$\text{if } v_{Cr_2} = V_r, \frac{dv_{Cr_2}}{dt} = \frac{1}{Cr_2} i_{L_b} \tag{6}$$

$$\text{if } v_{Cr_3} = V_p, \frac{dv_{Cr_3}}{dt} = \frac{1}{Cr_3}\left(i_{L_c} + i_{L_r} - i_{L_f}\right);$$

$$\text{if } v_{Cr_3} = V_q, \frac{dv_{Cr_3}}{dt} = \frac{1}{Cr_3}\left(i_{L_c} + i_{L_f} - i_{L_r}\right);$$

$$\text{if } v_{Cr_3} = V_r, \frac{dv_{Cr_3}}{dt} = \frac{1}{Cr_3} i_{L_c} \tag{7}$$

$$\frac{di_{L_f}}{dt} = \frac{1}{L_f}\left(V_p - V_q - v_{C_f}\right); \frac{di_{L_r}}{dt} = \frac{1}{L_r}\left(v_{C_f} - V_p + V_q\right) \tag{8}$$

Mode3 ($t_2 \le t < t_3$); $D_p$, $D_q$, $D_r$, $D_d$, and $S_1$ are on until $D_d$ is turned off. Similarly, the following equations, which are different from those of the corresponding system variables in mode 2, can be derived according to the changed operation modes. The equations related with the rest system variables remain in the same.

$$\text{if } v_{Cr_1} = V_r \text{ and } v_{Cr_1} \ge 0, \frac{dv_{Cr_1}}{dt} = \frac{1}{Cr_1}\left(i_{L_a} + i_{L_r} - i_{L_f}\right);$$

$$\text{if } v_{Cr_1} = V_r \text{ and } v_{Cr_1} < 0, \frac{dv_{Cr_1}}{dt} = \frac{1}{Cr_1}\left(i_{L_a} + i_{L_f} - i_{L_r}\right) \tag{9}$$

$$\text{if } v_{Cr_2} = V_r \text{ and } v_{Cr_2} \ge 0, \frac{dv_{Cr_2}}{dt} = \frac{1}{Cr_2}\left(i_{L_b} + i_{L_r} - i_{L_f}\right);$$

$$\text{if } v_{Cr_2} = V_r \text{ and } v_{Cr_2} < 0, \frac{dv_{Cr_2}}{dt} = \frac{1}{Cr_2}\left(i_{L_b} + i_{L_f} - i_{L_r}\right) \tag{10}$$

$$\text{if } v_{Cr_3} = V_r \text{ and } v_{Cr_3} \ge 0, \frac{dv_{Cr_3}}{dt} = \frac{1}{Cr_3}\left(i_{L_c} + i_{L_r} - i_{L_f}\right);$$

$$\text{if } v_{Cr_3} = V_r \text{ and } v_{Cr_3} < 0, \frac{dv_{Cr_3}}{dt} = \frac{1}{Cr_3}\left(i_{L_c} + i_{L_f} - i_{L_r}\right) \tag{11}$$

Mode4 ($t_3 \le t < t_4$); $D_p$, $D_q$, $D_r$, and $S_1$ are on until $V_{Cr}$, $V_{Cr_2}$, and $V_{Cr_3}$ become to be zero. Similarly, only the following equation is changed from that of mode 3, the rest remain in the same.

$$\frac{dv_{C_d}}{dt} = -\frac{1}{C_d} i_{L_r} \tag{12}$$

Mode5 ($t_4 \le t < t_5$); All diodes and $S_1$ are on except $D_d$ until the current through $L_r$ is equal to load current. Similarly, only the following equations are changed differently from those of mode 4, the rest remain in the same, except that equations related with $i_{L_r}$ and $i_{L_f}$ are those of the corresponding state variables in mode 2.

$$\frac{dv_{Cr_1}}{dt} = 0 ; \frac{dv_{Cr_2}}{dt} = 0 ; \frac{dv_{Cr_3}}{dt} = 0 \tag{13}$$

Mode6 ($t_5 \le t < t_6$); All switches are off until $D_d$ is turned on. The following equations are changed differently from those of mode 1, the rest remain in the same, except that $v_{c_d}$ equation is the same as equation (12).

$$\frac{di_{L_f}}{dt} = \frac{1}{L_f + L_r}\left(v_{C_d} - v_{C_f}\right); \frac{di_{L_r}}{dt} = \frac{1}{L_f + L_r}\left(v_{C_d} - v_{C_f}\right) \tag{14}$$

Mode7 ($t_2 \le t < t_3$); $D_p$, $D_q$, and $S_1$ are on until $V_r$ is equal to $V_p$ or $V_q$. All equations remain in the same, except that $v_{C_d}$ equation is the same as equation (12).

## 3. OPEN-LOOP CHARACTERISTICS

This section is prepared to devise a control loop suitable for the single-switch three-phase buck rectifiers. Basic operation characteristics of the system are dealt with under the open loop condition and the following analysis is done under the condition of the steady state operation.[4, 5]

First, when a pulse width modulation (PWM) method is applied to control the system at a fixed switching frequency, the output voltage of the system is controlled as shown in Fig.3. This figure shows that the duty ratio control technique limits the controlled range of the output dc voltage within the small variation. As a result, it can be said that the PWM method is not suitable for the single-switch three-phase buck rectifiers. It is concluded from this result that a pulse frequency modulation method is required to control the output dc voltage of the single-switch three-phase buck rectifiers.

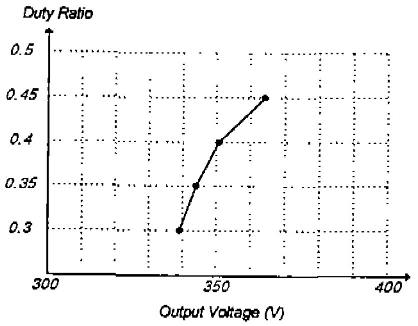


Fig.3. Control of the output voltage using the PWM

Secondly, the relation between the output voltage and the switching frequency is discussed in Fig.4. While the turn-on time of the switch remains on the fixed value, the output voltage is changed largely according to the variation of the operating switching frequency applied, especially compared with the results of the PWM method. As the switching frequency is increased, the resulting output voltage is also increased. It is concluded from the analysis above-mentioned that the pulse frequency control method is more suitable to the system than the pulse width control method.

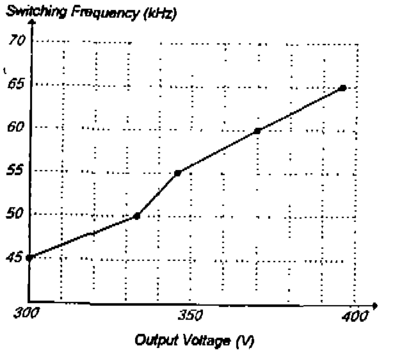


Fig.4. Control of the output voltage using the PFM

Third, the relation between the output power and the switching frequency is studied as shown in Fig.5. This figure shows that as the output power is increased in order to keep the output voltage at the approximately same value, the switching frequency is increased proportionally.

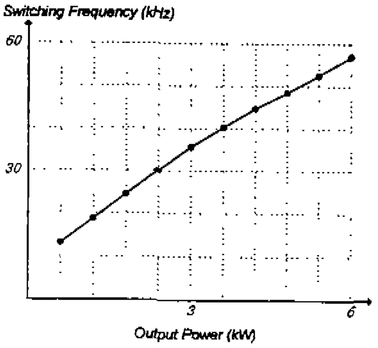


Fig.5. Relation between the output power and the switching frequency

## 4. CONTROL SCHEMES

Considering the results discussed in the previous section, a new control scheme suitable for the single-switch three-phase buck rectifiers can be established. Although the result of Fig.5 is obtained based on the steady state characteristics, the characteristics can be utilized to make up a proper control scheme for dynamically controlling the system. It is a basic concept for controlling the system that major portion of the value of the switching frequency is determined by the relation between the output power and the switching frequency which is obtained from the static characteristics. The rest of the value required for

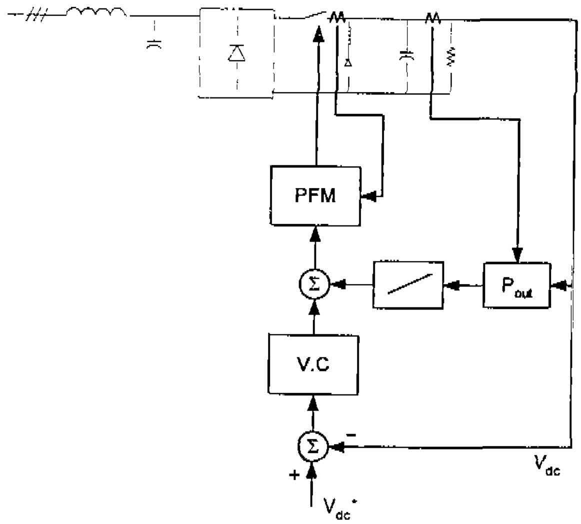


Fig.6. Overall control block diagram

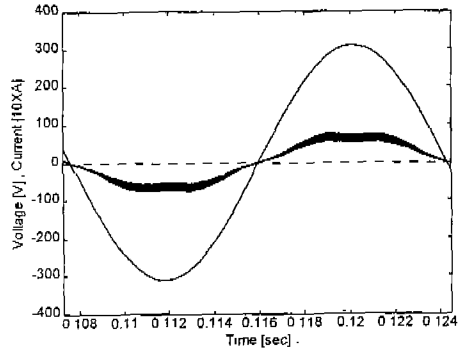
the switching frequency is set by the output voltage regulator which supports dynamic performances. The output power is calculated by the product of the output voltage and the output load current which are measured in the load terminal. Fig.6 shows the basic outline of the control scheme. It is also said that this control scheme involves a feedforward control loop against variation of the output load power. As the basic control action is not taken in the ac part of the system, but only the dc part, measuring the ac input-line currents and voltages are not needed.

In order that zero-current switching is guaranteed over all the range of the load variation, measuring the switch current is required in experiments. This control scheme can be implemented by using UC3825 PWM IC, which is provided with some modification device attached. Some additive circuits are designed to make up the functions of the frequency change and the fixed turn-on time.

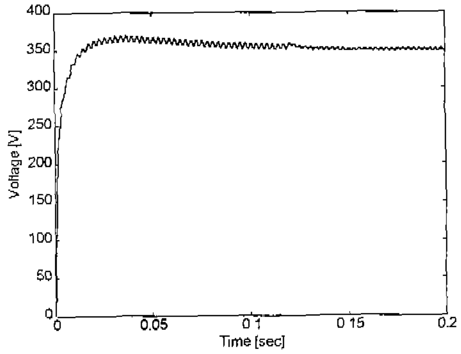
## 5. SIMULATIONS AND EXPERIMENTS

Several simulations and experiments are done to show validity of the proposed control scheme for the single-switch three-phase buck rectifiers. It is dealt with the input voltage of 380 Vac, 60 Hz, the output voltage of 350 Vdc, and the output power of 6 kw.

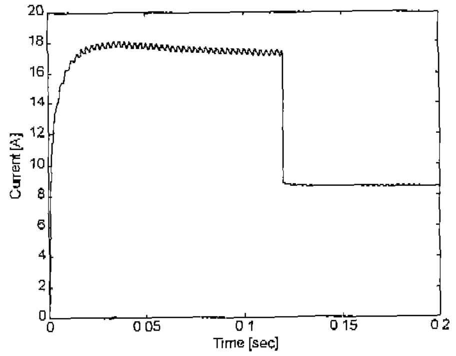
Fig.7(a) and (d) show simulated input voltage and current waveforms and principal waveforms respectively under 100% load. Fig.7(b) and (c) show dynamic response against step load change from 100% to 50% at t = 0.12sec. Fig.8(a) shows simulated input voltage and current waveforms under 10% load and Fig.8(b) and (c) are dynamic response against step load change from 10% to 50% at t = 0.12sec. It is seen in these figures that input line currents flow in the nearly sinusoidal waveform, maintaining the unity power factor. Dynamic responses of the regulated output voltage are satisfactory, especially illustrate a stable and fast response against the step load change due to a feedforward control loop. Fig.9 shows the experimented waveforms. Fig.9(a) shows input voltage and current waveforms and Fig.9(b) shows voltage and current waveforms of switch S1. Experimented results are obtained at the switching frequency 89kHz with constant switch on time under 100% load. The input filter inducters $L_a$, $L_b$, and $L_c$ of 1mH each and the output filter inductor $L_f$ of 2mH are used. The input side resonant tank capacitors $v_{Cr_1}$, $v_{Cr_2}$, and $v_{Cr_3}$ are connected in a delta configuration with 60nF each and the output side resonant tank capacitors $v_{C_d}$ is 120nF. The peak voltage and current of switch S1 are about 1200V , 70A respectively as shown in Fig.9(b).



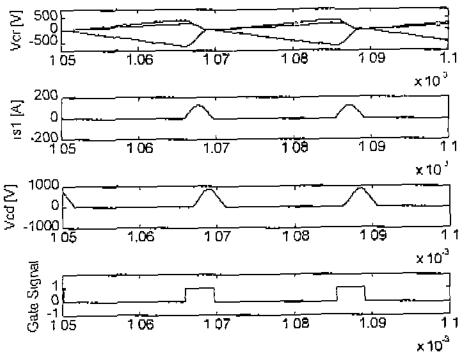
(a) Input voltage and current waveforms



(b) Output DC voltage response

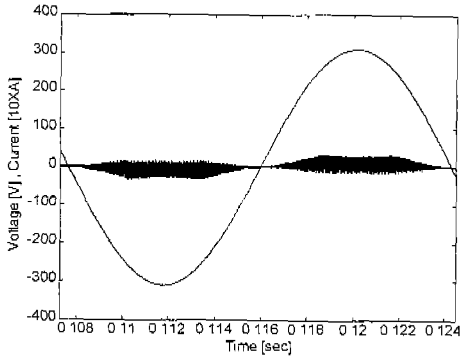


(c) Output DC current response

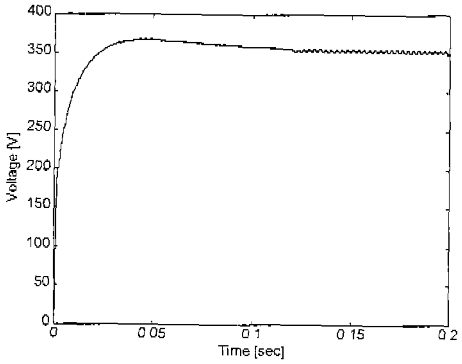


(d) Principal waveforms

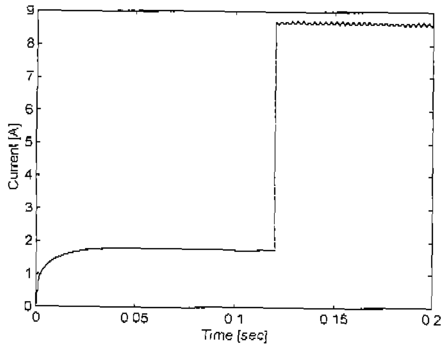
Fig.7. Simulation results under 100% load



(a) Input voltage and current waveforms

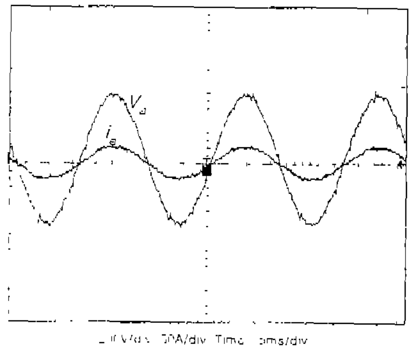


(b) Output DC voltage response

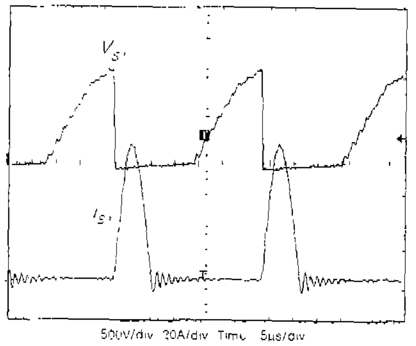


(c) Output DC current response

Fig.8. Simulation results under 10% load



(a) Input voltage and current waveforms



(b) Voltage and current of switch S1

Fig.9. Experimental results

## 6. CONCLUSION

A pulse frequency modulation method is studied for the single-switch three-phase buck rectifiers. The proposed frequency control scheme shows good performances in terms of the low total harmonic distortion of the input-line currents, the high power factor operation, and the dc output voltage regulation. The control scheme has a capability to keep the output voltage within the small fluctuation against the step change of the load applied.

## 7. REFERENCES

[1] Yungtaek Jang and R.W. Erickson, "New single-switch three-phase high-power-factor rectifiers using multiresonant zero-current switching," IEEE Trans. on Power Electronics, vol. 13, no. 1, pp. 194-201, 1998.

[2] Yungtaek Jang and M.M. Jovanovic, "Design considerations and performance evaluation of a 6 KW, single-switch, three-phase, high-power-factor, multiresonant, zero-current-switching buck rectifier," IEEE INTELEC Conference proceedings, paper no. 30-3, 1997.

[3] D.S.L. Simonetti, J. Sebastian, and J. Uceda, "Control conditions to improve conducted EMI by switching frequency modulation of basic discontinuous PWM preregulators," IEEE Power Electronics Specialist Conference, pp. 1180-1187, 1994.

[4] F.S. Dos Reis, J. Sebastian, and J. Uceda, "Applying FM control to PFP converters," IEEE Industrial Electronics Conference Proceedings, pp. 1814-1819, 1996.

[5] M.M. Jovanovic. D.M.C. Tsang, and F.C. Lee, "Reduction of voltage stress in integrated high-quality rectifier-regulators by variable-frequency control," IEEE Power Electronics Specialist Conference, pp. 569-575, 1994.