

## Research Article

### A Novel SVPWM Technology Used in PWM Rectifiers of WPGS

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**Abstract:** In order to achieve the transformation of electrical energy in Variable Speed Constant Frequency (VSCF) Wind Power Generation System (WPGS), a novel Space Vector Pulse Width Modulation (SVPWM) pulse trigger technology applied in high efficient PWM rectifier is proposed. Rectifier is an important part of WPGS and its performance affects the harmonic content and power factor of the power energy delivered to the grid. In order to improve the performance of PWM rectifier, a novel SVPWM pulse generator technology is proposed. Compared with other kinds of PWM pulse generator systems, Space Vector Pulse Width Modulation (SVPWM) has many advantages such as clear physical concept, simple algorithm, suitable for digital implementation, high voltage utilization, low harmonic content, low switches losses and simple hardware circuit.

**Keywords:** Harmonic content, power factor, PWM rectifier, space vector pulse width modulation, variable speed constant frequency, wind power generation system

## INTRODUCTION

The problems of traditional power energy are environmental pollution and the less and less quality, so the development and utilization of renewable energy sources such as wind power energy and solar power energy are attracting more and more attention. As the lower cost and abundantly global energy, wind power energy has been one of the most promising renewable energy that could be applied on a large scale. In traditional Wind Power Generation System (WPGS), Constant Speed Constant Frequency (CSCF) technology was adopted and wind turbine ran at fixed speed. The power generator couldn't capture the optimum operating point by following the changed wind speed, leading to the declination of generator efficiency. The efficiency of adopted wind turbine is also low because its wear and tear increases with the changing wind speed. The wind energy resources are waste for not being made full use of. To overcome the disadvantages of CSCF technology mentioned above, the Variable-speed Constant Frequency (VSCF) technology is applied in modern and future WPGS. In VSCF, Doubly-fed Induction Generator (DFIG) or Direct-Drive (DD) Permanent Magnet Synchronous Generator (PMSG) technology can be employed to capture maximum wind energy and they both have wide application scale. By controlling its inner power electronics devices, the VSCF technology can not only provide high quality power energy with the required frequency to the grid, but also flexibly adjust the active power and reactive power sent to or absorbed from the grid. In WPGS based on VSCF, rectifier,

which is used to convert AC voltages and currents to DC ones, is the necessary device achieved by power electronics elements (Li, 2009; Zheng *et al.*, 2011).

Harmonic problems in power system are mainly caused by the application of power electronics equipments like diode or thyristor rectifiers, which absorb non-sinusoidal currents from the Common Connected Point (CCP) of the grid. High power factor rectifiers subsequently occur and have been used in many occasions. Pulse Width Modulation (PWM) rectifiers, which can sent to or absorb from almost sinusoidal AC current and realize unity power factor, have been widely investigated and some of them based on Voltage Source Converter (VSC) have already been put into practice (Zhang and Zang, 2005; Zhang, 2007; Zhao and Han, 2012). For PWM rectifiers based on VSC, there are a variety of the trigger pulse generation methods. These methods are applied to improve the quality of the voltages and currents of the rectifiers from different perspectives. Reference (Gao, 2004) demonstrated the realization process of SPWM pulse generator based on CPLD. Although it is relatively simple and easy, SPWM generator technology has many disadvantages such as high harmonic content and low voltage utilization rate. Liu *et al.* (2002) analyzed Selective Harmonic Elimination (SHE-PWM) technology used in the VSC pulse generator system. SHE-PWM technology can eliminate the low-order harmonics of the AC output voltages and currents, but it eliminates lower order harmonics at the expense of pulsing high voltage harmonics. For Selective Harmonic Elimination (SHE-PWM) technology, the frequencies of

voltage harmonics concentrate near the switching frequency.

This study presents the Space Vector Pulse Width Modulation (SVPWM) technology which is a novel pulse generator strategy and triggers the switches in the rectifiers to control the AC currents and the DC voltage. SVPWM technology has many advantages such as clear physical concept, simple algorithm, suitable for digital implementation, high voltage utilization, low harmonic content, low switches losses and simple hardware circuit. The DSP-based SVPWM pulse generator technology is introduced and used to trigger PWM rectifiers to improve its static and dynamic properties. The proposed SVPWM technology is mainly used in the three-phase PWM rectifier.

### THE MATHEMATICAL MODEL OF PWM RECTIFIER

The three-phase PWM rectifier is consisted of three legs, each of which has two switches with anti-parallel diodes as shown in Fig. 1.

In order to simplify analysis process, it is assumed that the three-phase voltage of the CCP in the grid is symmetrical, stable and interior resistance is zero, three-phase linking resistance R and L are the same values respectively, switches loss and on-state voltage is negligible, affection of distributing parameters is negligible, switching frequency of the rectifier is high enough (Zhang and Zang, 2005; Zhang, 2007). For PWM rectifiers bas].The mathematical mode of the three-faze PWM rectifier in Fig. 1 is shown in (1) and (2).

$$\begin{cases} L \frac{di_a}{dt} + Ri_a = e_a - (v_{dc}s_a + v_{N0}) \\ L \frac{di_b}{dt} + Ri_b = e_b - (v_{dc}s_b + v_{N0}) \\ L \frac{di_c}{dt} + Ri_c = e_c - (v_{dc}s_c + v_{N0}) \end{cases} \quad (1)$$

$$C \frac{dv_{dc}}{dt} = i_a s_a + i_b s_b + i_c s_c - \frac{v_{dc} - e_L}{R_L} \quad (2)$$

Equation (1) and (2) is mathematical model of the three-phase PWM rectifier in three-phase static frame. In order to simplify the controller design of PWM rectifier, the three-phase PWM rectifier's mathematical model in two d-q rotation frame is shown in (3).

$$\begin{cases} L \frac{di_q}{dt} + \omega L i_d + R i_q = e_q - v_{dc} s_q \\ L \frac{di_d}{dt} - \omega L i_q + R i_d = e_d - v_{dc} s_d \\ C \frac{dv_{dc}}{dt} = \frac{3}{2} (i_q s_q + i_d s_d) - i_L \end{cases} \quad (3)$$

Equation (3) is a nonlinear model system and it is required to be linear zed. Three new variables such as  $u$ ,  $u_d$ ,  $u_q$  are defined in (4) and the improved model of three-phase PWM rectifier is shown in (5).

$$\begin{cases} u = v_{dc}^2 \\ u_d = e_d - v_{dc} s_d = e_d - v_d \\ u_q = e_q - v_{dc} s_q = e_q - v_q \end{cases} \quad (4)$$

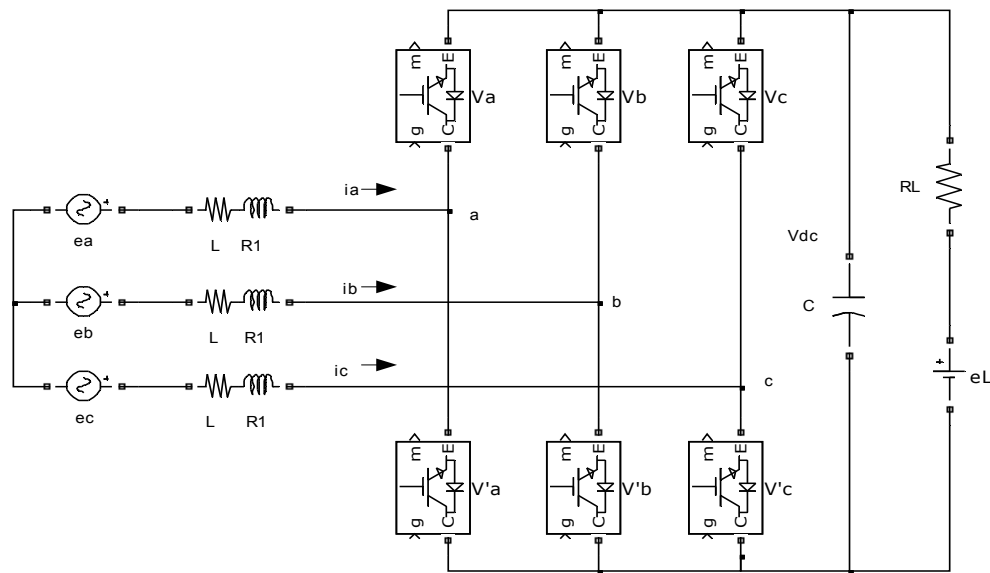


Fig. 1: The main circuit of three-phase PWM Rectifier

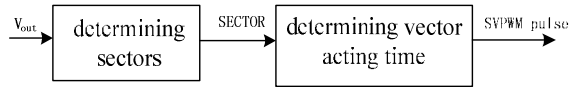


Fig. 2: The block diagram of SVPWM

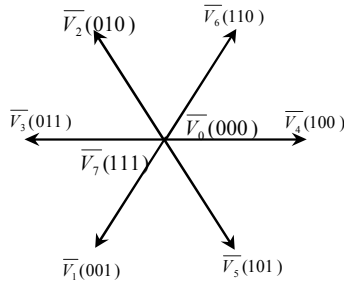


Fig. 3: Maps of space vectors

$$\begin{cases} L \frac{di_q}{dt} = -\omega L i_d - \frac{R}{L} i_q + \frac{1}{L} u_q \\ L \frac{di_d}{dt} = -\omega L i_q + \frac{R}{L} i_d + \frac{1}{L} u_d \\ \frac{du}{dt} = -\frac{2}{R_L C} u + \frac{3}{C} e_d i_d + \frac{3}{C} e_q i_q \end{cases} \quad (5)$$

**THE PRINCIPLE OF SVPWM PULSE GENERATOR TECHNOLOGY**

For Space Vector Pulse Width Modulation (SVPWM) technology, two orthogonal voltage vectors  $V_d$ ,  $V_q$  in the two-dimensional rotating coordinate system act as the real time references, which are transformed from the desired three phase voltages in rectifier. The key of the SVPWM technology is to determine which sector the vectors are in and how long each vector works (Tejas *et al.*, 2011; Kumar and Gokulakrishnan, 2011). The block diagram of SVPWM technology is shown in Fig. 2.

There are 8 working models in the switching pattern of the rectifier arms. The 8 working

Table 1: The working time of each vector

Sector	1	2	3	4	5	6
t1	Z	Y	-Z	-X	X	-Y
t2	Y	-X	X	Z	-Y	-Z

models correspond to eight space voltage vectors  $\bar{V}_0(000) \sim \bar{V}_7(111)$ , wherein  $\bar{V}_1(001) \sim \bar{V}_6(110)$  are called effective vectors and each of their amplitudes is  $U_{dc}$ ,  $\bar{V}_0(000)$ ,  $\bar{V}_7(111)$  are called zero vectors and each of their amplitudes is zero, as shown in Fig. 3.

The sector determination of vectors distribution and working time of each main vector and auxiliary vector in SVPWM are shown in Table 1. When the sector of the required synthetic vector and the working time of corresponding main vector, auxiliary vector and zero vectors are obtained, SVPWM wave can be generated.

**IMPROVED SVPWM FIXED-FREQUENCY CONTROL STRATEGIES**

The working principle of improved SVPWM control strategy is proposed in this study, which is same to the traditional SVPWM control strategy. The fundamental frequency cycle of three-phase AC voltage is divided into six sectors, each of which is 60° electrical angle.

The voltage polarities in each sector of improved SVPWM and traditional SVPWM are different because the starting times of each fundamental frequency cycle of improved SVPWM and traditional SVPWM are different. As shown in Fig. 4, in the improved SVPWM control strategy, the characteristic of the sector division is that in each interval, any two phases are ensured to have the same signs and they are with contrary to the third one. In order to ensure high power factor, the phase angles of the input currents and the input voltages should be controlled to be equal. SVPWM switching algorithm is shown in Table 2. To the sector I for example, the  $v_{sa}$ ,  $v_{sb}$  are positive and  $v_{sc}$  is negative, so  $i_{sa}$ ,  $i_{sb}$  are positive and  $i_{sc}$  is negative. In this working

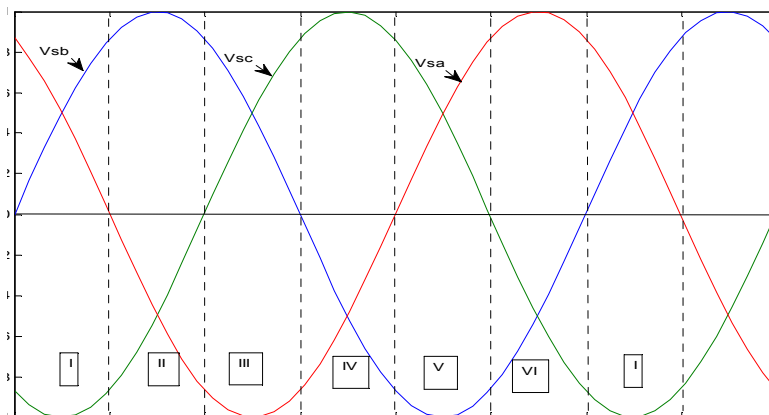


Fig. 4: Distribution sector of power phase voltage in Improved SVPWM

Table 2: SVPWM switching algorithm

Sector	Vector	Conduction Rate
I	$V_0$	$d_a = \frac{2V'_a + V'_b}{V_{dc}}$
	$V_1$	$d_b = \frac{V'_a + 2V'_b}{V_{dc}}$
	$V_2$	$d_c = 0$
	$V_7$	$d_a = 1 + \frac{2V'_a + V'_c}{V_{dc}}$
II	$V_2$	$d_b = 1$
	$V_3$	$d_c = 1 + \frac{V'_a + 2V'_c}{V_{dc}}$
	$V_0$	$d_a = 0$
III	$V_3$	$d_b = \frac{2V'_b + V'_c}{V_{dc}}$
	$V_4$	$d_c = \frac{V'_b + 2V'_c}{V_{dc}}$
	$V_7$	$d_a = 1 + \frac{2V'_a + V'_b}{V_{dc}}$
IV	$V_4$	$d_b = 1 + \frac{V'_a + 2V'_b}{V_{dc}}$
	$V_5$	$d_c = 1$
	$V_0$	$d_a = \frac{2V'_a + V'_c}{V_{dc}}$
V	$V_5$	$d_b = 0$
	$V_6$	$d_c = \frac{V'_a + 2V'_c}{V_{dc}}$
	$V_7$	$d_a = 1$
VI	$V_6$	$d_b = 1 + \frac{2V'_b + V'_c}{V_{dc}}$
	$V_1$	$d_c = 1 + \frac{V'_b + 2V'_c}{V_{dc}}$

mode, as the current does not flow through  $S_a, S_b, S_c, VD_a, VD_b$  and  $VD_c$ , the voltage vector can be synthesized through controlling the state of  $S_a, S_b, S_c$ .

In order to reduce switches losses, the two-phase modulation method is adopted. The working length of each phase in one cycle is one third, on which the switches maintain turn-on or turn-off and do not change and the working time of zero vector is controllable. The proposed modulation method is superior to conventional modulation method in reducing switches losses. It can be seen that the conduction rates and the basic vectors used for the synthesis of the required voltage vector are consistent whatever PWM rectifier operates in rectifier or inverter state (Yin, 2006).

### IMPLEMENTATION OF THE SVPWM PULSE GENERATOR

Digital Signal Processor (DSP) has some advantages such as good accuracy and stability. The functions of DSP-based digital controller are achieved

via software programs and hardware construction. When the hardware circuits are designed correctly, several control algorithms can be programmed respectively. Modifying software programs to meet the requirements has some characteristics of lower costs, shorter development cycles and good efficiency. To determine a simple, reasonable and effective control algorithm to efficiently compensate reactive power, different control algorithms are validated. The idea of only modifying software programs gives room to the improvement and optimization of controller and it can reduce costs and save development debugging time.

**DSP used in SVPWM technology:** The TMS320LF2407 chip, a member of the TMS320C2000 generation of digital signal processor controllers, is one of the fixed-point DSPs. The 2407 offers the enhanced TMS320 DSP architectural design of the C2xx core CPU for low-cost, low-power and high-performance processing capabilities. Several advanced peripherals, optimized for digital motor and motion control applications, have been integrated to provide a true single-chip DSP controller. While code-compatible with the existing C24x DSP controller devices, the 2407 offers increased processing performance (30 MIPS) and a higher level of peripheral integration. The 2407 offers an array of memory sizes and different peripherals tailored to meet the specific price/performance points required by various applications. Flash devices of up to 32K words offer a cost-effective reprogrammable solution for volume production. Note that Flash-based devices contain a 256-word boot ROM to facilitate in-circuit programming. The 2407 also includes ROM devices that are fully pin-to-pin compatible with their Flash counterparts. The 2407 offers two event manager modules which have been optimized for digital motor control and power conversion applications.

In order to generate SVPWM signals, many registers should be set. The register ACTRA is used to define the output mode of the compared output pin. The register COMCONA is used to enable the comparison operations and determine SVPWM mode and set the reloading conditions of CMPR1, 2, 3 to underflow. Many parameters in each PWM cycle should be determined by AC side voltages. For two adjacent vectors  $U_x$  and  $U_x + 60$ , parameters T1, T2, T3, are loaded to the 14th~12th bits of ACTTRA according to  $U_x$  and the value 1 is load to the 15th bit of ACTRA and then half of T1 is loaded to register CMPR1, the half of (T1+T2) is loaded to register CMPR2. Generally, the formula  $CMPR1 \leq CMPR2 \leq T1PR$  should be satisfied in Space Vector PWM. The register CMPR3 is not used in SVPWM technology and it can be used in other timed events.

**Accuracy of the main controller:** The accuracy of controller is mainly related with the hardware

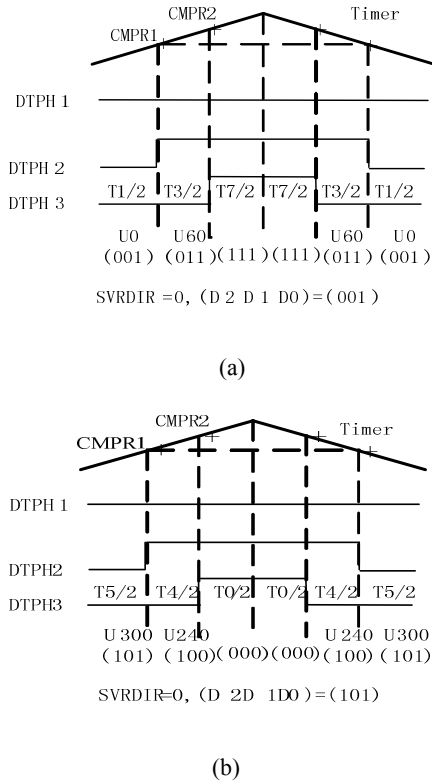


Fig. 5: The waveform of symmetric space vector PWM

components. The accuracy of A/D converter in TMS320LF2407 is 10 bits and the converting results store in the high 10 of 16 bits. As an example of the sampling current: while current is sinusoidal amount, the converting results store in the high 10 of 16 bits after left-moved 10 times. The current is transformed to sample value in the range of 0~1024 and then the value is in the range of -512~+512 after subtracting 512, expressed as FD00~01FF. The sampling results can be expressed as Q15 format to improve the process precision. The specific process is as follows.

The maximum value of sampling current is 15.6A (correspondingly the sampling resistance is 320Ω). The benchmark of current is 40A when it is standardized. The output of ADC is expressed as Q15 format as follows:

$$i = RES \times \frac{15.6}{512} \times \frac{32767}{40} \quad (6)$$

where,

RES = The value of ADCRESULTn.

In the course of programming  $K = \frac{15.6}{512} \times \frac{32767}{40} = 24.992371$  RES × K is the value of ADCRESULTn in Q15 format. In order to improve the accuracy of set points multiplication, the value of K is also expressed in Q15 format. The benchmark of K is

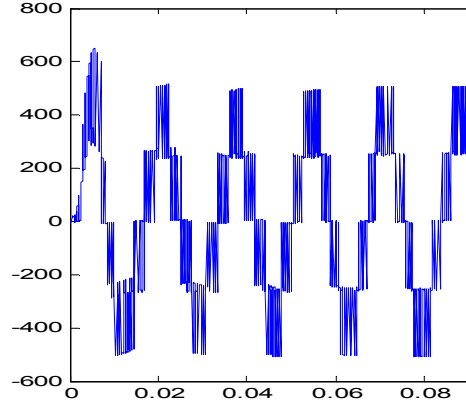


Fig. 6: Phase voltage of VSC

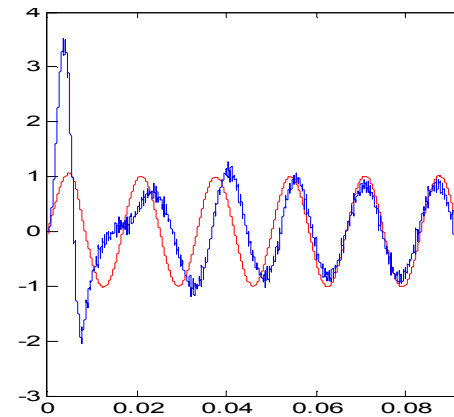


Fig. 7: Voltage and current in phase A

$2^5 = 32$  when it is standardized.  $RES \times 2^5 \times \frac{K}{2^5} \times 32767$

is achieved when  $K' = \frac{K}{2^5} \times 32767$  is multiplied by

RES after it is left-moved 5 times. Then ADCRESULTn can be expressed as Q15 format.

### SIMULATION RESULTS AND ANALYSIS

According to setting the registers in the previous section, the resulting SVPWM waveform is center symmetrical in each PWM cycle and this method is called the symmetric SVPWM method, shown in Fig. 5.

Hump waveform is obtained through filtering PWM output voltage waveform, which indicates that the pulses generated by the proposed pulse system to trigger the main circuit rectifier arms is proper and reasonable and the desired sinusoidal voltages can be obtained. The proposed pulse system is applied to PWM rectifier and many results are obtained. Figure 6 is the phase voltage of rectifier AC side. Figure 7 is the waveform of voltage and current filtered in the same phase. After three cycle times, the voltage and current are in the same phase and the power factor is very high.

## CONCLUSION

To overcome the disadvantages of CSCF technology, the Variable-speed Constant Frequency (VSCF) technology is applied in modern and future WPGS. In VSCF, Direct-Drive (DD) Permanent Magnet Synchronous Generator (PMSG) technology can be employed to capture maximum wind energy and have wide application scale. A pulse trigger system based on TMS320LF2407A DSP is designed and the used DSP chip contains hardware PWM pulse generator circuit. Compared with other kinds of PWM pulse generator systems, Space Vector Pulse Width Modulation (SVPWM) has many advantages such as clear physical concept, simple algorithm, suitable for digital implementation, high voltage utilization, low harmonic content, low switches losses and simple hardware circuit.

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