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Comparison of Modulation Techniques of a Grid Side Converter in a Wind Energy Conversion System

In this article, the grid side converter of a low power on-grid WECS has been investigated where two Pulse Width Modulation techniques –Space Vector Pulse Width Modulation (SVPWM) and Discontinuous Pulse Width Modulation (DPWM)- applied to compare switching losses of semiconductors and THD of the system. For this purpose, SIMULINK/MATLAB simulation was run to calculate the THD of the grid current in inverter operation at the grid side converter. Also the switching instances of the active elements have been determined and Visual Basic based program has been used to calculate the switching losses at these instances. The results have shown that, SVPWM has better THD performance over DPWM at the same switching frequency. However, by carefully selecting the switching frequency of DPWM higher than that of SVPWM without increasing the switching losses of DPWM beyond the switching losses of SVPWM, it is possible to find switching frequency values at which DPWM can have better THD performance.

Key words: Discontinuous Pulse Width Modulation, Switching Loss of Semiconductors, Total Harmonic Distortion, Wind Energy Conversion Systems

Usporedba tehnika modulacije mrežnog pretvarača u sustavu pretvorbe energije vjetra. U ovom članku se istražuje mrežni pretvarač male snage na mreži WECS. Primijenjene su dvije tehnike modulacije širine pulsa – modulacija širine pulsa korištenjem vektorskog polja (SVPWM) i isprekidana modulacija širine pulsa (DPWM) kako bi se usporedili gubici prilikom prebacivanja poluvodiča i THD-a sustava. Iz tog razloga napravljena je Simulink/Matlab simulacija kako bi se izračunao THD mrežne struje prilikom inverterskog rada mrežnog pretvarača. Također slučajevi prebacivanja aktivnih elemenata su ustanovljeni i napisan je program u Visual Basicu kako bi se izračunao gubitak u tim slučajevima. Rezultati pokazuju da SPWM ima bolje performanse THD-a u odnosu na DPWM prilikom iste frekvencije prebacivanja. Međutim, pažljivim odabirom više DPWM frekvencije prebacivanja od SVPWM-a te uz izbjegavanje povećanja gubitaka prebacivanja kod DPWM-a iznad gubitaka prebacivanja SVPWM-a moguće je naći frekvenciju prebacivanja kod koje DPWM ima bolje THD performanse.

Ključne riječi: Isprekidana modulacija širine pulsa, Gubici prebacivanja kod poluvodiča, Ukupna harmonijska distorzija, Sustavi pretvorbe energije vjetra

1   INTRODUCTION

Wind energy has become one of the world's fastest growing energy sources due to its clean and renewable nature. Reduced mechanical stress and aerodynamic noise and controllability to operate at its maximum power coefficient over a wide range of wind speeds to obtain a larger energy capture from the wind are the main reasons to build variable speed systems in recent years. Extracting the maximum power from the available wind power has become very important in order to use the available energy as efficient as possible [1-2].

The extracted maximum available power from WECS is either stored in batteries or flows to the mains by means of conversion to DC or AC electrical energy with an efficient method. The efficiency increase of on grid WECS depends on the reduction of the power losses of the circuit elements such as semiconductors, power inductors etc. However, the harmonic content of the current flowing to the utility grid as well as the acoustic noise induced by AC inductors have to be lowered. In this case, the switching frequency should be increased to 15 to 20kHz range which causes increased switching losses [3]. To increase the total efficiency of the system one can implement different topologies among the system like 2-Level Voltage Source Converters (VSC) with a special PWM method or 3-Level VSC which has the inherent advantages over the former one. Studies in [4-7] state that 3-Level topologies have

the advantage of better voltage waveforms, lower total harmonic distortion, lower power device ratings and lower dV/dt stress. However, in 3-Level topology the complexity of the system increases due to higher number of elements used. Also the neutral point voltage balance should be considered to satisfy the performance and the reliability of the system [8].

On the other hand, special PWM methods like DPWM scheme can help to reduce the switching losses of semiconductors in a two Level VSI [9-10]. The on-grid converters are expected to be high power density. Besides, the current flowing to the grid from the converter should create THD lower than 5% [11]. The selected PWM has also a direct influence on current harmonic content [8], [12].

In this study, a wind energy conversion system (WECS) has been considered and the effects of the modulation scheme on the current harmonics and the switching losses of IGBTs on the grid side have been investigated. For this purpose, MATLAB/SIMULINK program has been used to calculate current harmonics and knowing the switching instances, pulse-by-pulse switching losses of the IGBTs in the converter have been calculated by a visual basic based software.

2 MATHEMATIC MODEL OF THE GRID SIDE CONVERTER

Figure 1. illustrates the converters of the WECS. L type filter has been used for the grid connection. e_a, e_b and e_c show the AC source voltages while V_a, V_b and V_c show the converter AC terminal voltages. V_{dc} is the DC-link bus voltage. i_a, i_b and i_c are the phase currents. S_1, S_2 and S_3 denotes the status of each switch on each leg. $S_i = 1$ if T_{2i-1} is on, $S_i = 0$ if T_{2i} on and index i can be equal one of 1,2,3. The voltage equations for each phase can be shown depending on the status of each switch as follows:

$$L\frac{di_a}{dt} + Ri_a + e_a = V_{dc}(S_1 - \frac{1}{3}\sum S_i)$$
$$L\frac{di_b}{dt} + Ri_b + e_b = V_{dc}(S_2 - \frac{1}{3}\sum S_i) \quad (1)$$
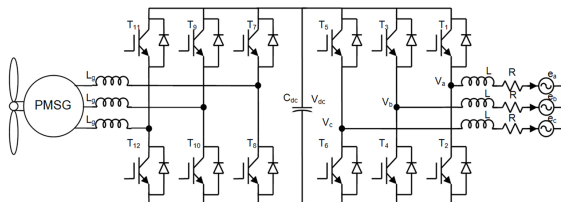$$L\frac{di_c}{dt} + Ri_c + e_c = V_{dc}(S_3 - \frac{1}{3}\sum S_i)$$

Fig. 1. WECS with two back to back converters

Due to time variant and nonlinear nature of these equations, the variables have to be transformed into synchronized rotating frame for easier implementation with the

following transformation matrices (2) and (3) [13]. Variable x can be taken as current, voltage or any other three phase variable to be transformed into the synchronized rotating frame.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} x_q \\ x_d \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \quad (3)$$

3 PULSEWIDTH MODULATION TECHNIQUES

There are two widely applied Pulse-width modulation (PWM) techniques: regular or natural sampled PWM method and space vector modulation (SVM) method. In the former method, pulses are generated by comparing reference voltages with a triangular wave which defines the switching instances.

SVM is an alternative method for determining switched pulse widths. By having the degree of freedom for pulse placement, it can help to achieve harmonic performance gains. [9-10], [14-19].

3.1 Space Vector Pulse Width Modulation

A three phase converter (Fig 1.), has 8 permissible switching states, two of which are named as zero states where outputs shorted to negative or positive DC-link. The remaining six states can be considered to form stationary vectors in the α-β complex plane (Fig 2.). Each stationary vector is $\pi/3$ angle apart constructing a hexagon and two zero vectors are located in the origin. The magnitude of each six vectors is (2/3)Vdc.

An arbitrary output voltage can be constructed by averaging a number of space vectors within one switching period. For instance, considering that reference output is in the first sector (in first $\pi/3$ sector), the first two active vectors can be used to calculate the durations to build the reference output voltage (Fig. 3).

$$V = V_a + V_b = V_1\frac{t_1}{T} + V_2\frac{t_2}{T} + V_0\frac{t_0}{T} \quad (4)$$

$$t_1 = \frac{V_a}{V_1}T \quad (5)$$

$$t_2 = \frac{V_b}{V_2}T \quad (6)$$

$$t_0 = T - (t_1 + t_2) \quad (7)$$

t0 is used as the zero vector to fill the remaining gap for period. Switching losses can be kept minimum by allowing only one turn-on and turn-off during one switching period (Fig. 4). In order to have minimal harmonics, pulse pattern is constructed symmetrically to have the zero vectors distributed conveniently between V0 and V7 vectors [13].
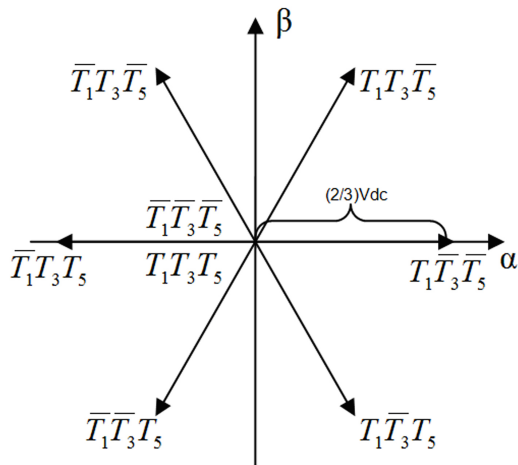
Fig. 2. *Space Vector diagram of a two level inverter*

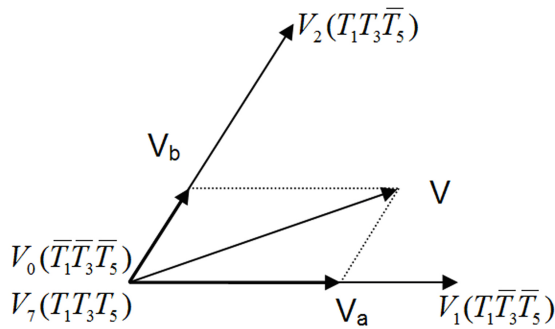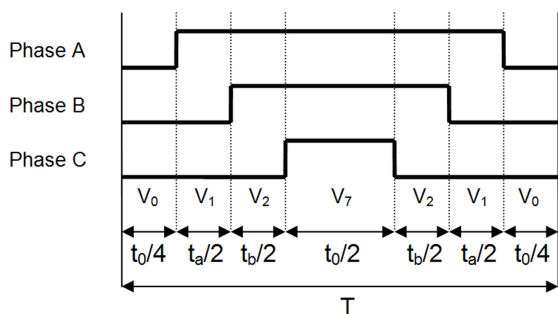Fig. 3. *Construction of a reference vector*

Fig. 4. *Construction of pulse pattern for minimum harmonic distortion*

3.2   Discontinuous Pulse Width Modulation

The freedom to place the zero space vector to create different PWM implementations can eliminate switching instances by either allowing the outputs connected to the positive or negative DC link for duration of 1/3 switching period which allows the average switching frequency to become 2/3 of the actual switching frequency [10].

These discontinuous pulse width modulation schemes can be grouped into three types depending on the intervals of the nonswitched segment: DPWM120, DPWM60, DPWM30 (Fig. 5, Fig. 6, Fig. 7).
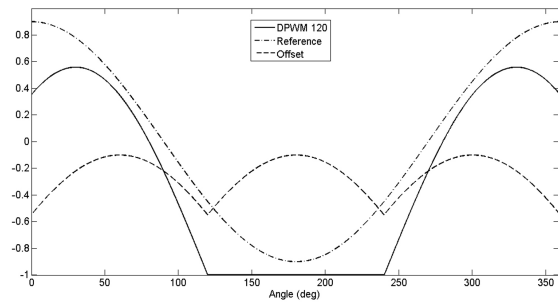

Fig. 5. *Construction of DPWM 120*

60° discontinuous modulation has the advantage of centering the nonswitching periods for each phase leg symmetrically around the positive and negative peaks of its fundamental reference voltage. This will lead to minimized switching losses. It is also possible to place each 60° nonswitching period anywhere within the 120° region where the appropriate phase leg reference voltage is the maximum/minimum of the three-phase set such that switching losses for capacitive and inductive loads for a maximum 30° leading and lagging power factor respectively can be minimized [10], [16-20].
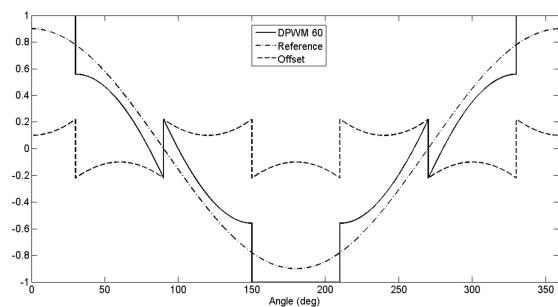

Fig. 6. *Construction of DPWM 60*

4   IMPLEMENTATION OF CONTROL STRATEGY TO CONVERTER OPERATION

4.1   Control Strategy

In order to see the differences between DPWM and SVPWM on loss performance on the switching devices a Matlab/Simulink simulations have been done by adopting direct current control strategy (Fig. 8). For this purpose, two closed loop PI regulators have been used to control the
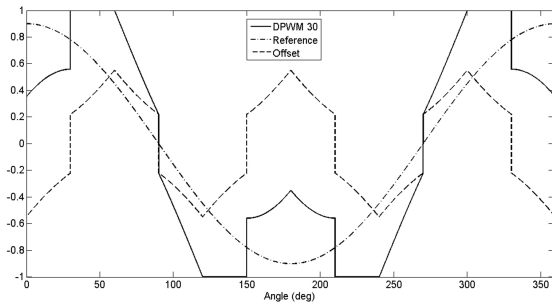
Fig. 7. Construction of DPWM 30

Fig. 9. Block diagram illustration of the controller

DC-link voltage and the AC side currents (Fig. 9). q-axis reference signal has been produced from the DC-link Voltage controller. Feed-forward decoupling values have been added to the q-d current controllers in order to form the reference v_d and v_q modulation signals.

$$i_q* = \left(K_p + K_i \int dt\right)\left(V_{dc}* - V_{dc}\right)$$
$$v_q* = v_q - \left(K_p + K_i \int dt\right)\left(i_q* - i_q\right) - \omega L i_d \quad (8)$$
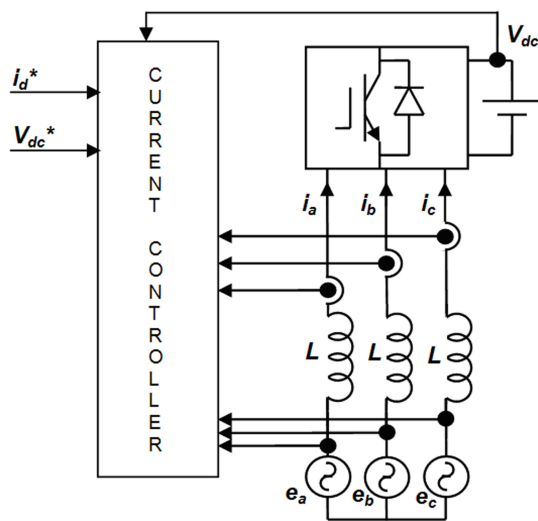$$v_d* = -\left(K_p + K_i \int dt\right)\left(i_d* - i_d\right) + \omega L i_q$$

Fig. 8. Controller for the Grid Side Converter

4.2 Implementation of DPWM60° for Loss Reduction

Having the nonswitched $60°$ interval around the vicinity of the maximum value of the current will decrease the switching losses further due to the occurrence of switching at lower current values compared with SVPWM.

The phasor diagram of phase voltage (V'), phase current (I') and the converter phase-output voltage (V_{ph}) are shown in Fig. 10. Due to the filter inductance there is a
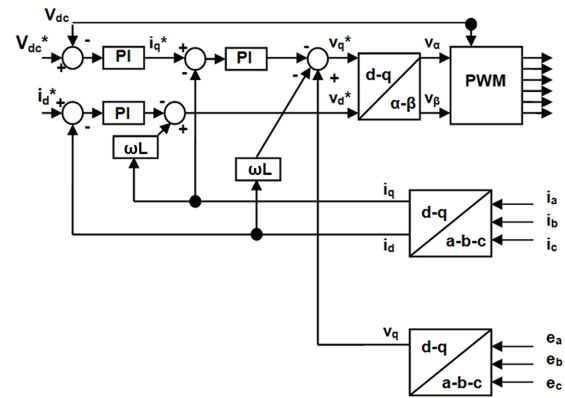
phase shift of Θ degrees between the phase voltage and the converter phase-out voltage. In order for the reference voltage to be created at the vicinity of the maximum phase current, the nonswitched areas have to be shifted Θ degrees (Fig. 11). As a result the nonswitched sectors of the DPWM occur at the maximum values of the phase currents.

Figure 12. illustrates the DPWM $60°$ modulation signal, Phase voltage and the phase current. As seen, the voltage and current are in phase and the non switched $60°$ intervals of the modulation signal occurred at the vicinity of the phase current to decrease the switching losses.
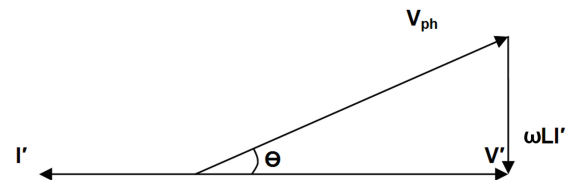

Fig. 10. The phasor diagram of phase voltage (V'), phase current (I') and the converter phase-output voltage (V_{ph})
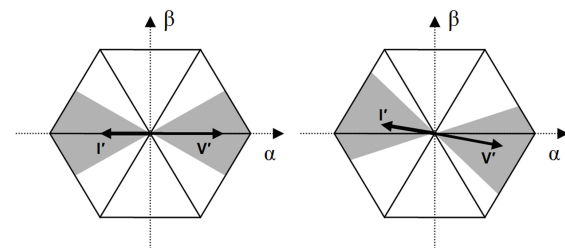

Fig. 11. Shifting the reference voltage for Θ degrees to have the non switching interval at the vicinity of the maximum phase current

5   COMPARISON OF SVPWM AND DPWM SIMULATION RESULTS

For the simulation of the system, 10,5kW power has been considered. Rectifier operation for the grid converter has been simulated for SVPWM and DPWM. Parameters of the simulation are as follows: DC-link voltage is 700V, line frequency is 50Hz, Line-to-line voltage is 380Vrms, sampling time is 500nsec, DC-link capacitance is 2200μF. During the simulations, the grid side filter has been changed from 1mH to 5mH.

In order to calculate the switching losses of IGBTs, 50A/1200V three phase module has been selected for real application loss performance reference. The switching energy of individual IGBTs was calculated by pulse-by-pulse approach based on the datasheet E_{on} and E_{off} values. For this purpose, current values were recorded and the corresponding E_{on} and E_{off} energies were calculated depending on the DC-link voltage. The average switching loss of any IGBT was calculated by integrating these energy values over one output current cycle.
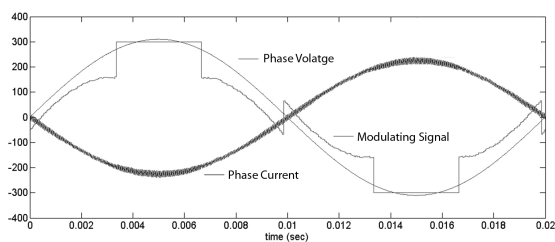

Fig. 12. DPWM 60° modulation signal, Phase voltage and the phase current

Five different switching frequency values along with five different filter inductance values have been simulated in each of DPWM and SVPWM simulations. Fig. 13 and Fig. 14 show the THD values calculated by SIMULINK for different switching frequencies and corresponding filter inductance values for DPWM and SVPWM respectively. Fig. 15 shows the comparison of switching losses of DPWM and SVPWM at switching frequencies where THD calculations were also made. Since the calculation results have shown that the differences between the switching loss values are very low for different inductance values at the same switching frequency and same PWM scheme, in Fig. 14, only one inductance value is considered for the illustration of each PWM scheme switching losses.

Table-1 summarizes the comparison of THD and switching loss performances of DPWM and SVPWM with 2mH of output filter at selected switching frequencies. As expected, it is seen that SVPWM has better THD performance over DPWM when same switching frequency
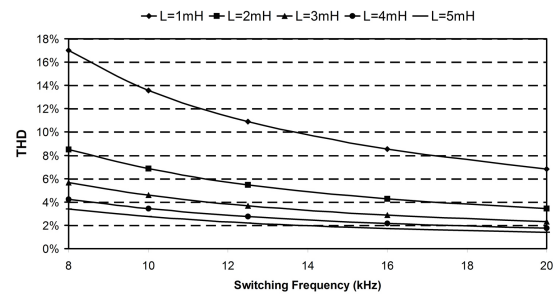

Fig. 13. THD values calculated by SIMULINK for DPWM

values are considered. However, if the switching frequency of SVPWM is fixed and the switching frequency of DPWM is increased, it is possible that at some switching frequency values, THD performance of DPWM can get better than that of SVPWM while DPWM still has better switching loss performance. For instance, from Table-1, when DPWM switching frequency is selected as 16kHz and SVPWM switching frequency is selected as 10kHz, DPWM has better switching losses performance and THD advantage over SVPWM.
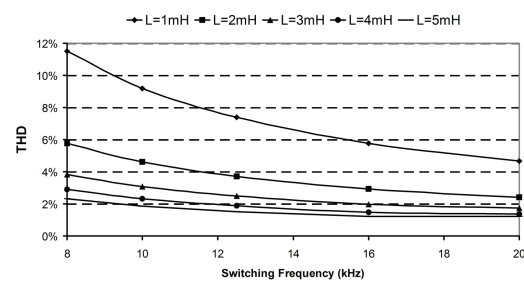

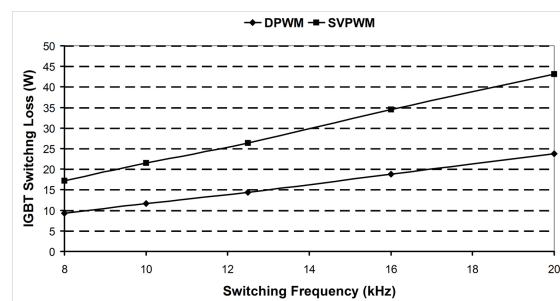*Fig. 14. THD values calculated by SIMULINK for SVPWM*

Fig. 15. Comparison of switching losses of DPWM and SVPWM

Table 1. DPWM and SVPWM performance comparison with 2mH output filter inductance

Switching frequency	PWM Method			
	DPWM		SVPWM	
	Switching losses per IGBT (W)	THD	Switching losses per IGBT (W)	THD
8kHz	9.35	8.52%	17.26	5.76%
10kHz	11.89	6.85%	21.57	4.61%
12.5kHz	14.73	5.48%	26.77	3.70%
16kHz	18.98	4.28%	34.54	2.92%
20kHz	24.03	3.44%	43.16	2.42%

6 CONCLUSION

Extracting maximum power in Renewable Energy Systems is the target for efficient use of the energy sources. However, the need for an efficient method to let the power flow to the storage devices or to the grid has also a high importance. In this study, the grid side converter PWM control scheme has been investigated and the switching losses occurred in IGBTs created by these two PWM methods were compared with the help of MATLAB/SIMULINK. The results have shown that, SVPWM has better THD performance over DPWM at the same switching frequency. However, by carefully selecting the switching frequency of DPWM higher than that of SVPWM without increasing the switching losses of DPWM beyond the switching losses of SVPWM, it is possible to find switching frequency values at which DPWM can have better THD performance.

7 ACKNOWLEDGEMENTS

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