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전기차용 전력변환장치의 펄스 폭 변조 기법 분석

Analysis of Pulse Width Modulation Schemes for Electric Vehicle Power Converters

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Abstract - In order to overcome the problem of fossil fuel energy, electric vehicle (EV) has been used in recent years. The important issues of EV are driving distance and lifetime related to EV efficiency. A voltage source converter is one of the main components of EV which can be operated with various pulse width modulation (PWM) schemes such as continuous PWM schemes and discontinuous PWM schemes. These PWM schemes will cause the effects on the efficiency of converter system and the lifetime of EV. Therefore, this paper proposes an analysis of the PWM schemes for the power converter on the EV. The objective is to find out a best solution for the EV by comparing the total harmonic distortion (THD) and transient response between the various PWM schemes. The operation of traction motor on the EV with the PWM schemes will be verified by using Psim simulation program.

Key Words : Electric vehicle, Pulse width modulation, Permanent magnet synchronous machines, Voltage source converter

1. Introduction

One of the sources of pollutant emission into the atmosphere comes from the vehicles that use fuels of the diesel oil and gasoline. Besides, the fossil fuel is also depleted by the excess exploitation of human. In order to overcome these problems, many countries have recommended the usage of renewable energy source and the electric vehicle (EV). Recently, the rapid development of the electric motor and battery technologies has promoted the use of EV. Especially, Jeju special self-governing province has a plan, namely Carbon Free Island Jeju by 2030, in order to reduce CO2 emission from fossil fuel energy. In this plan, the local government will supply about 371,000 EVs by 2030 in order to replace 100% of conventional cars that use the fossil fuel. These EVs are supplied energy by the renewable energy sources and the conventional power plants. The objective is to use the renewable energy sources as a prior energy source. The EV must be designed to meet special requirements of consumer such as cost, driving distance and lifetime [1]. Among them, the lifetime of traction motor will be significantly affected by the output voltage quality that relates to the pulse width modulation (PWM) schemes for the voltage source converter (VSC) on the EV [2]-[7]. In [2], the authors have shown that the electric motor behaves as a "loudspeaker" when the output voltage of the power converter contains the harmonic components. In addition, the harmonic components also affect electrical and mechanical sub systems on the EV [4]-[6]. Besides, the PWM frequency can cause the temperature on the IGBT and then reduces the lifetime of the power converter [7]. As a result, the quality of the output voltage as well as the PWM schemes for the power converter are important issues. There are some PWM schemes that have been researched by many authors over the world. The PWM schemes can be classified into two categories [8]. First one is continuous PWM (CPWM) schemes including sinusoidal PWM (SPWM) scheme, space vector PWM (SVPWM) scheme, and third harmonic injection PWM (THIPWM) scheme. Other one is discontinuous PWM (DPWM) schemes, for example, DPWMMIN scheme and DPWMMAX scheme. However, these PWM schemes are only researched in separated situations [9]-[13]. Therefore, this paper proposes an analysis of PWM schemes for the power converter on the EV. The objective is to find out a best solution for the EV by comparing total harmonic distortion (THD) and transient response between the various PWM schemes.

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2. Pulse Width Modulation Schemes

In the EV system, the role of VSC is to convert DC power source of the battery system into AC power source supplied for the motor drive. It is operated by turning on/off the IGBTs based on the PWM schemes. In this paper, six PWM schemes for the VSC on the EV such as SPWM scheme, sinusoidal-THIPWM scheme (S-THIPWM), triangular-THIPWM scheme (T-THIPWM), SVPWM scheme, DPWMMIN scheme, and DPWMMAX scheme will be analyzed and compared each others.

2.1 Sinusoidal Pulse Width Modulation Scheme

The SPWM is one of the conventional PWM schemes for the VSC because of its simple implementation. In this PWM scheme, the gating signals are generated by comparing a carrier waveform (triangular signal) to a sinusoidal waveform (reference signal) as seen in Fig. 1.

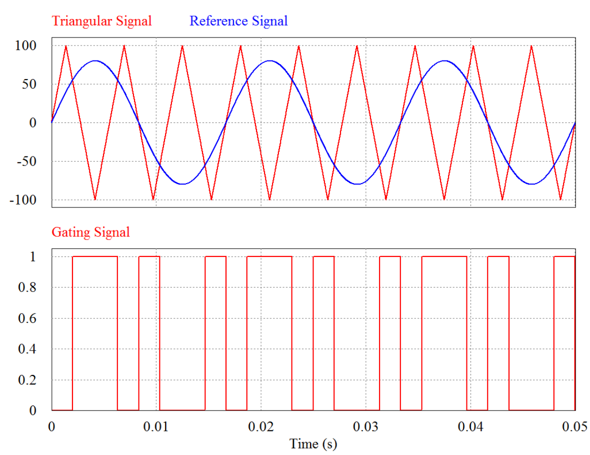
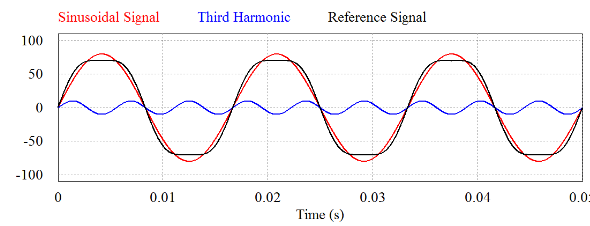


Fig. 1 Sinusoidal pulse width modulation scheme

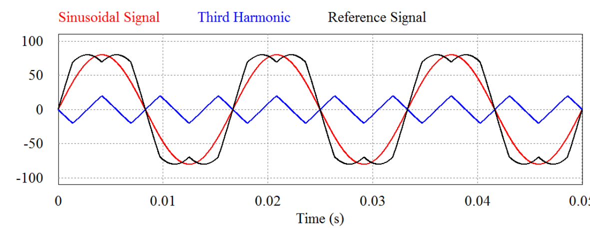
2.2 Third Harmonic Injection Pulse Width Modulation Scheme

The THIPWM schemes are almost similar to the SPWM scheme. The difference is that the reference signal is made by injecting a third harmonic component into the sinusoidal signal. The objective is to improve the gain of the output voltage. There are two kinds of the THIPWM scheme, namely S-THIPWM scheme and T-THIPWM scheme [9, 10]. Figs. 2(a) and (b) shows the reference signals of the S-THIPWM scheme and T-THIPWM scheme. The triangular signal is the same with the SPWM scheme.

- In Fig 2(a), the reference signal is obtained by adding a sinusoidal third harmonic signal to a sinusoidal signal at fundamental frequency.
- In Fig. 2(b), the reference signal is obtained by subtracting a triangular third harmonic signal from a sinusoidal signal at the fundamental frequency.

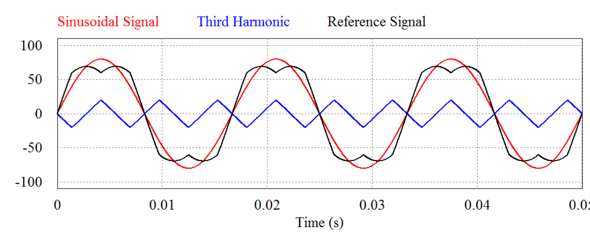


(a) Sinusoidal-THIPWM

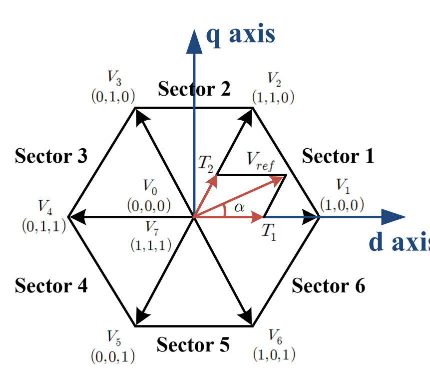


(b) Triangular-THIPWM

Fig. 2 Third harmonic injection PWM schemes



(a) Reference waveform



(b) Space vector representation

Fig. 3 Space vector pulse width modulation scheme

2.3 Space Vector Pulse Width Modulation Scheme

The SVPWM scheme is shown in Fig. 3(a). It is quite different from the SPWM and THIPWM schemes. The power converter can be driven to eight unique states as illustrated in Fig. 3(b). The control strategies are implemented in digital systems. The SVPWM scheme has many advantages over the conventional PWM scheme such as high modulation index, perfect digital operation and low switching losses [11, 12].

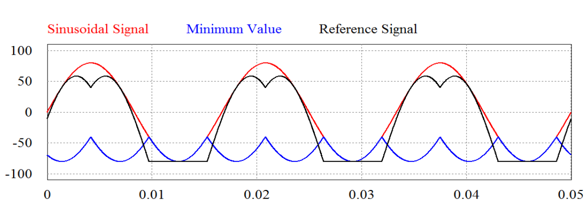
2.4 Discontinuous Pulse Width Modulation Scheme

The DPWMMIN and DPWMMAX schemes are shown in Figs. 4(a) and (b), respectively. These PWM schemes have an advantage of reducing the effective switching frequency over a fundamental period [13]. The idea of this scheme is clamping a phase to either side of the DC voltage. The clamping voltage is done either at maximum voltage or minimum voltage. This scheme is an unsymmetrical scheme that clamping voltage is only done during one of the half cycles for 120^0. The reference signals of the DPWMMIN and DPWMMAX schemes are calculated as

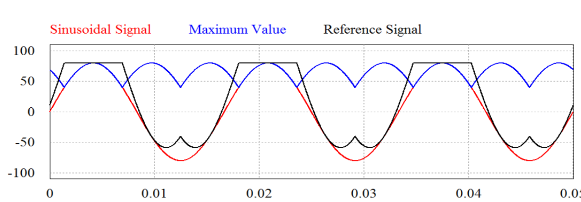
$$v_{refj\_\min} = v_j - \frac{V_{dc}}{2} - \min(v_a, v_b, v_c) \quad (1)$$

$$v_{refj\_\max} = v_j + \frac{V_{dc}}{2} - \max(v_a, v_b, v_c) \quad (2)$$

where, j = a, b, c denotes the phase A, B, C. $v_{refj\_\min}$ and $v_{refj\_\max}$ are the reference voltages of phase j corresponding to the DPWMMIN and DPWMMAX schemes. v_j is the voltage of the phase j. V_{dc} is the DC voltage.



(a) Minimum discontinuous PWM



(b) Maximum discontinuous PWM

Fig. 4 Discontinuous pulse width modulation scheme

3. Modeling of Electric Vehicle

A simple modeling of the EV is shown in Fig. 5. It consists of a battery system, traction motor, and VSC system. In this study, the traction motor is a PMSM that can operate as a motor or a generator. The battery is modeled from Shepherd non-linear battery model. The charging and discharging voltages of the battery system are calculated as [14]

$$V_{charge} = E_0 + K \times \frac{Q}{Q - it} \times (it + i_{ref}) + A exp(-B \times it) \quad (3)$$

$$V_{discharge} = E_0 + K \times \frac{Q}{it - Q} \times i_{ref} - K \times \frac{Q}{Q - it} + A exp(-B \times it) \quad (4)$$

where, V_{charge} and $V_{discharge}$ are the charging and discharging voltages. E_0 is battery constant voltage. K is polarization constant. Q is battery capacity. A is exponential zone amplitude. B is exponential zone time constant inverse. it is actual battery charge, and i_{ref} is filtered current.

The stator voltages of the PMSM are expressed in the synchronous rotating reference frame as

$$v_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \quad (5)$$

$$v_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_r \lambda_d \quad (6)$$

where, v_d and v_q are the dq-axis stator voltages. i_d and i_q are the dq-axis stator currents. λ_d and λ_q are dq-axis stator flux linkages. R_s is the resistance of stator winding. ω_r denotes the rotor speed.

The torque of PMSM is a function of the current and rotor speed as

$$T_{em} = \frac{3}{2} P(\lambda_d i_q - \lambda_q i_d) \quad (7)$$

$$\lambda_d = L_d i_d + \lambda_m \quad (8)$$

$$\lambda_q = L_q i_q \quad (9)$$

where, L_d and L_q are the dq-axis stator inductances. P is number of pole pairs. T_{em} is the electromechanical torque developed by the PMSM. λ_m is the flux linkage from rotor magnets linking stator.

The VSC consists of 6 IGBTs and six anti-parallel diodes that are arranged as seen in Fig. 5. The VSC is responsible for the control of the PMSM on the EV.

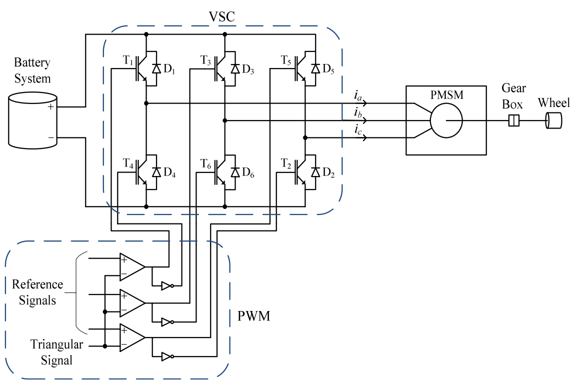
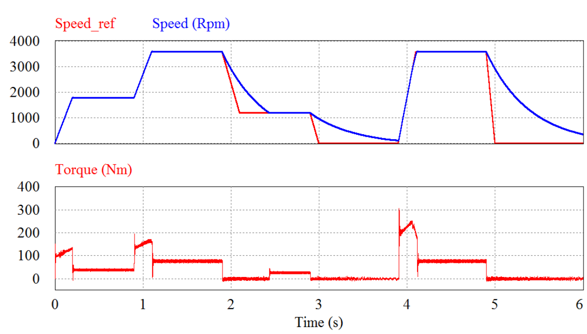


Fig. 5 Simple modeling of EV

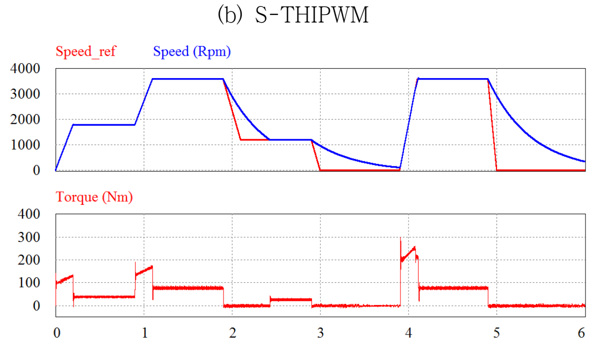
4. Simulation Results

In the study case, the operation of PMSM on the EV is performed at the same condition in six cases that correspond to six PWM schemes as analyzed in Section 2. Table 1 shows the parameters of a PMSM on the EV. The simulation results obtained by using Psim simulation program are shown in Fig. 6. The PMSM is operating with the variable speed. This is similar to the real conditions when the EV moves on the street. The objective of the simulation results is to verify the effect of the PWM schemes to the operation of PMSM on the EV. Generally, the operations of the PMSM in six PWM schemes are almost similar each others. There are the transient responses when the PMSM is accelerated and decelerated

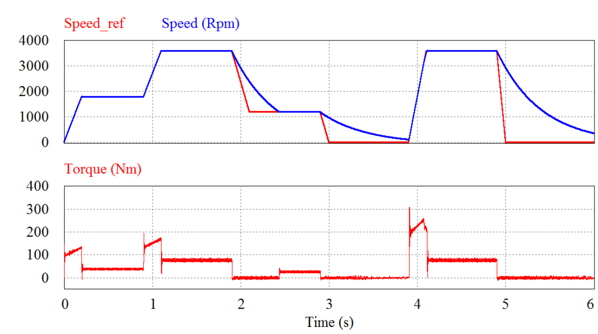


(a) SPWM

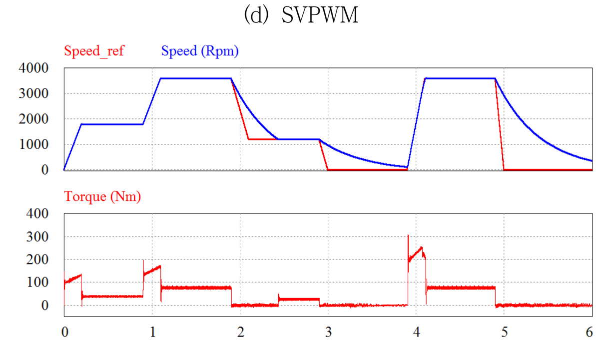
(b) S-THIPWM



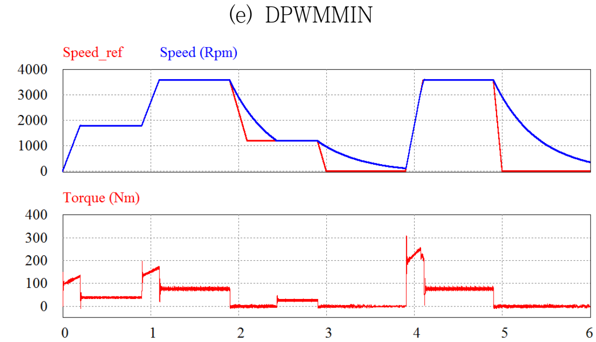
(c) T-THIPWM



(d) SVPWM

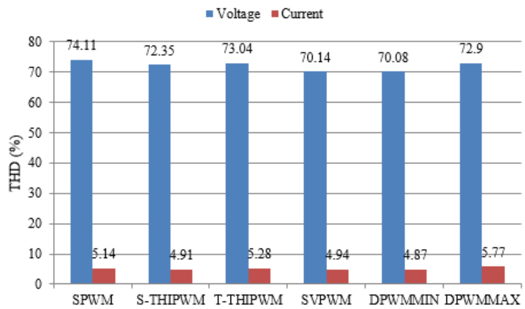


(e) DPWMMIN

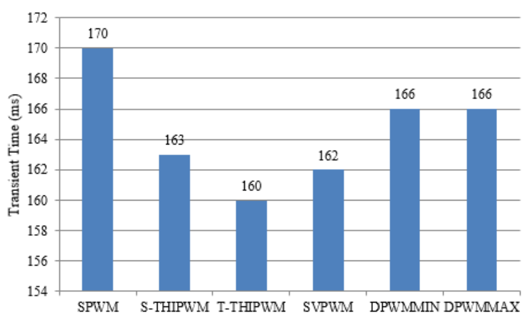


(f) DPWMMAX

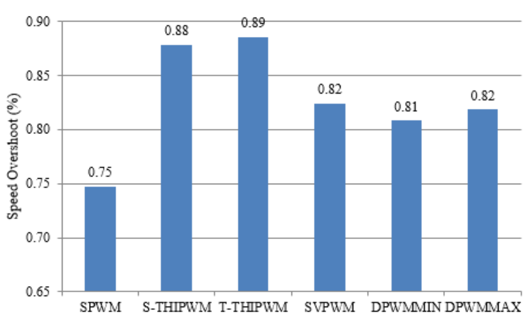
Fig. 6 The operation of EV with various PWM schemes



(a) THDs of the voltage and current



(b) Transient time of rotor speed



(c) Overshoot of rotor speed

Fig. 7 THD of the output voltage and transient response of the rotor speed

because of the inertia moment. The PMSM needs a higher torque to reach a higher reference speed at the accelerating time as seen in bottom figures of Figs. 6(a)-(f). The output voltage of the VSC is a three-level voltage waveform that contains the harmonic components. These harmonic components will cause the negative effects as well as reducing lifetime of the VSC and the PMSM.

The THD of the output voltage and transient responses of the rotor speed in six PWM schemes are shown in Fig. 7. These data are achieved when the PMSM on the EV operates at the rated speed of 3600 rpm. The THDs are high because this system does not use any filter as seen in Fig. 7(a). This is to obtain an exact comparison between six PWM schemes. With the minimum clamping voltage, the DPWMMIN shows a best performance in THDs of the voltage and current among the PWM schemes with the value of 70.08% and 4.87%, respectively. It has been well understood that the harmonic components will cause the losses and heating on the PMSM. Thus, a lower THD can improve the losses and then the lifetime of the PMSM as well as the EV. Besides, the DPWMMIN scheme can also reduce the switching frequency of the IGBTs and leads to a reduction of losses on the VSC. This can improve the efficiency of the VSC. The transient responses of the rotor speed in six PWM schemes are not too much different. The error between the maximum transient time (SPWM) and minimum transient time (T-THIPWM) is only about 10 ms (Fig. 7(b)). The overshoots of the rotor speed are almost less than 1% of rated speed as shown in Fig. 7(c).

Table 1 Parameters of the EV model

Item	Value
Motor power	80 kW
Rated voltage	176 V
Rated current	296 A
Rated speed	3600 rpm
Switching frequency	8 kHz
Battery capacity	52 Ah

5. Conclusion

This paper has analyzed and compared the PWM schemes for VSC on the EV. In order to evaluate the effectiveness of the PWM schemes, the driving schedule of the EV was adapted as a operating condition of variable speed. The simulation results have demonstrated that the operation of EV is almost similar in six PWM schemes with a given driving schedule. However, there is a difference in the THDs of the output voltage and current. The DPWMMIN scheme has shown a best performance for the EV among six PWM schemes in the concept of THDs. Thus, the lifetime and losses of the PMSM can be improved with the DPWMMIN scheme. The transient responses between six PWM schemes including the transient time and overshoot of the rotor speed are not significantly different.

Acknowledgement

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