# A Study on the High Performance PWM Technique for a Propulsion System of Railway.

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**Abstract** - This paper presents a high performance low switching PWM technique for the propulsion system of railway such as subway and high speed train. In order to achieve the continuous voltage control to six-step and a low harmonics with low switching frequency under 500Hz, the synchronous PWM technique is combined with a space vector overmodulation and implemented by using DSP. Improved performance and a validation of proposed method are showed by the digital simulation and the experimental results using a 1.65MVA IGBT VVVF inverter and inertia load equivalent to 160 tons railway vehicles.

## 1. Introduction

Due to the development of power electronics, the variable speed control system in motor drives, which use high class semiconductor devices for power has to be eased to control output about load in addition to energy saving. Therefore, it is being actively used in the industry today. Resulting from this, induction motors and inverters, which are variable speed control systems are being used fully in the propulsion control systems of railroad vehicles. However, compared to the development of the control technology of the propulsion systems, the development of the semiconductor device for power which materializes the propulsion system and generates an optimum system design but the PWM technology are deficient; resulting in a lacking performance of the propulsion control system for railroad vehicles. In general, for the reduction in size of the traction motor, the design of the rated voltage is based on a 6 pulse inverter output. Therefore, the inverter requires an overmodulation PWM method and must guarantee a continuous output up to 6 pulse. However, semiconductor devices for power which can be applied to today's propulsion systems for railroad vehicles are mostly the GTO (Gate Turn-Off) Thyristor which has a limit in the switching frequency of a couple hundred Hz. The recently developed 3300V / 1200A level IGBT (Insulated Gate Bipolar Transistor) device is also limited to use under 1kHz. Due to these switching frequency limits, the conventional overmodulation control in the propulsion control system must operate the PWM control with RMS voltage size patterns set in advanced. This method not only result in numerous harmonics in the output current, but also cause a great current change of the load and input because of discontinuous voltage vectors during the mode change. These problems not only depreciate the propulsion system's efficiency and control, but reduce the life span and cause fatal effects in the machinery [1][2].

In this paper, using the PWM method progressed in the propulsion control system for railroad vehicles, the harmonics of output have been ensured. This led to the proposal of a PWM method with a superior variable speed control. This method grafted the SVM (Space Vector Modulation) overmodulation method and the synchronous PWM method to form the operating switching frequency of under 500Hz. It has been compared with the previous PWM method to show the improvements. For verifying it's perforance the experiment carried out using both a 1.65 MVA level railroad vehicle propulsion control inverter with a 3300V / 1200A IGBT and the inertial load with an equivalent modelling of railroad vehicles 160 tons. A 32bit DSP was used for the control system.

## 2. Conventional Switching Pattern

High capacity inverters like ones used in railroad vehicle propulsion systems are limited to switching frequencies of a couple hundred Hz.

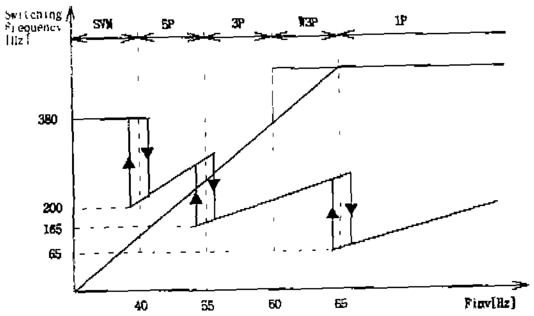
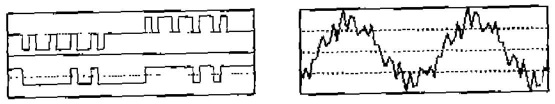


Fig. 1 Conventional PWM pattern.

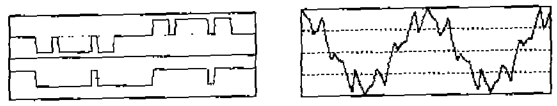
This increases the on/off time and dead time of the semiconductor device for power and excessive switching loss results in the size increase of the semiconductor's cooling system.

Generally, if the switching frequency is low, the fundamental component of the output voltage can not have a half sampling time symmetry and in the output, the AC voltage turns out lower than the fundamental order. This substance has a fatal effect on the power conversion system consisting of a low order resonance frequency. Therefore, when the modulation frequency is low, the PWM can be carried synchronously with fundamental wave, in general its boundary value of about 19-21. For the synchronuos PWM, the modulation frequency keeps the switching frequency at a constant and therefore decreases as the standard frequency increases. Also, as the modulation index increases, the modulation frequency decreases due to the controlling difficulties caused by the minimum on/off time of the switching device. Finally, at 1 pulse mode, the modulation index led to 1. However, as discussed before, when proceeding with modes of different modulation numbers, continous control of the voltage vector is difficult and noise is produced. Controlling the PWM with many modes in process is complex and therefore, recently the synchronous PWM was run when the modulation number was 9 or lower than 5 [1]. Fig. 1 shows the PWM control method for present subway propulsion control systems with a overmodulation PWM. The synchronous overmodulation PWM carried out at over 5 of modulation frequency.

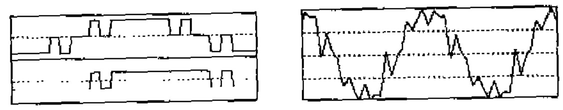
The asynchronous triangular modulation method is used for the linear control area, beyond that, the synchronous PWM method is used. The synchronous PWM formation for each mode is shown in Fig. 2. For the PWM waveform, the voltage size control is according to the change in width of the notch shown in the phase voltage.



(a) voltage and current waveform for 5 pulse mode



(b) voltage and current waveform for 3 pulse mode



(c) voltage and current waveform for wide 3 pulse mode

Fig. 2 Output voltage and current waveform for each PWM mode.

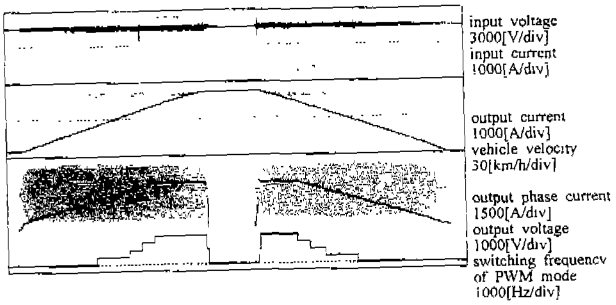


Fig. 3 Continuous current control performance by conventional PWM method.

In other words, the notch width and RMS voltage of the waveform are directly proportional. This proportion differs with each mode. However, as shown in Fig. 1, even areas lower than the limit switching frequency like the procedure from 5 pulse to 3 pulse have mode activities. This happens with the voltage limit of the mode's control capability. Therefore, high capacity semiconductor device require a minimum on/off time. For even larger voltage output, the two 5 pulse modes were changed to the one 3 pulse mode and the 3 pulse mode changed to the wide 3 pulse mode in order to control the voltage until the 6 step with no notches.

This kind of overmodulation pattern as seen in Fig. 2 does not fully use the switching frequency designed for limit of the voltage control and results in excess harmonics in the output current. As shown in Fig. 3, because of the discontinuous voltage of the mode procedure at acceleration or deceleration of railway vechiles, there exists an excessive input/output current causing a deficiency in the output control and fatal effects in the system. As these excessive substances start to critically effect the system, recently as shown in Figure 1, the process from the 3 pulse mode to the 6 step shows a 5-8% voltage dip. To endure this voltage difference, the PWM was run without the wide 3 pulse mode which has the greatest voltage discontinuity [2].

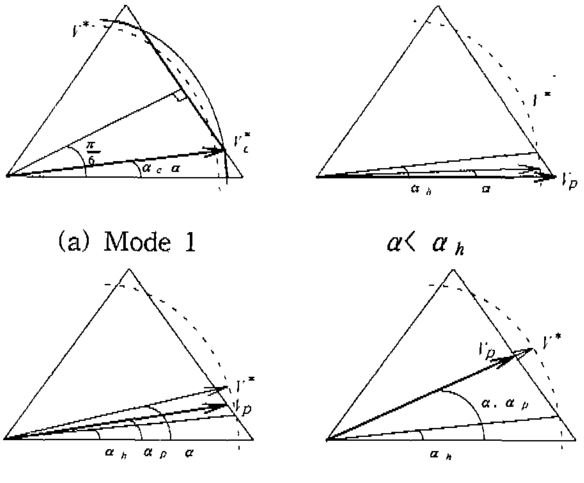
## 3. Overmodulation PWM Method with High Efficiency and Low Frequency

The conventional PWM, according to the different frequencies, has a totally different composition for the control function and output waveform,. Therefore, it is difficult to control, the voltage vector for each mode becomes discontinuous due to the difference between the control function and waveform, and the designed controllable switching frequency is not efficiently used creating excessive harmonics. Through this paper, a PWM method which can solve these problems is proposed and formulated. A low frequency synchronous PWM method with the low switching frequency using the space voltage overmodulation PWM method is described.

### 3.1. Space Voltage Vector Overmodulation Algorithm [3]

Generally, in the modulation area, the voltage size with the PWM is either the same as the voltage desired or different. The case where they are linearly the same is called the linear control area and if not, called the overmodulation area. Consequently, in the overmodulation area, the voltage desired and output value are not linearly the same. In order to output the desired value, FFT analysis must be done to calculate a separate control function to form the standard wave into the desired voltage. This new control function is set as an equation (1) and is shown in two ways according to the modulation index. Mode 1 is when the desired voltage and phase are same but with different sizes and when the size of mode 1 reaches its maximum, a change of phase is needed, as in mode 2.

$$M_i = \frac{V^*}{\frac{2}{\pi} V_{dc}} \tag{1}$$



(a) Mode 1 $\alpha < \alpha_h$

$\alpha > \alpha_h$ $\alpha = \frac{\pi}{6}$

(b) Mode 2

Fig4. New voltage reference for overmodulation

Here $V^*$ is the fundamental phase voltage.

Mode 1 : $0.906 < M_i < 0.955$

Mode 2 : $0.955 < M_i < 1.0$

The controllable instantaneous voltage from the output during the PWM control is the voltage within the triangle. As seen in Figure 4(a), when the size of the reference phase voltage goes beyond the triangle, the area deviated from the hexagon is compensated by forming a new control function from the vertex. The angle at which this new control function meets the triangle is $\alpha_c$. However, if the reference voltage becomes greater than the allowable compensated area, it can no longer be processed and the output voltage is compensated by changing the stand-by time at the vertex. For the 6 step, which has the maximum stand-by time, the new control function changes the vertex position [3][4].

In the overmodulation mode 1, using the Fourier Series with the voltage wave form which gives the desired fundamental component, the following formula is used to calculate the compensation angle $\alpha_c$ for each modulation index. The relationship between the modulation index and compensation angle is shown in equation (2).

$$\begin{aligned} Mi &= \frac{2}{\sqrt{3}}[\frac{1}{\sqrt{3}}\left\{\frac{9}{2\pi}(1+\sqrt{3}\,\alpha_c)\cos\alpha_c\right. \\ &\left.+(\frac{9}{2\pi}\alpha_c-3-9\frac{\sqrt{3}}{2\pi})\sin\alpha_c\right\}+\frac{3}{2}\alpha_c] \end{aligned} \tag{2}$$

The new fundamental voltage $V_c^*$ using the compensation angle $\alpha_c$ is shown in equation (3).

$$V_c^* = \frac{V_{dc}}{\sqrt{3}\cos(\frac{\pi}{6} - \alpha_c)} \tag{3}$$

In the overmodulation mode 2, using the Fourier Series with $M_i$ and the holding angle at the vertex $\alpha_h$ gives the equation (4).

$$M_i = \frac{\sin(\frac{\pi}{6} - \alpha_h)}{\frac{\pi}{6} - \alpha_h} \tag{4}$$

According to $\alpha_h$, the triangle of the space vector is divided into three parts and as in equation (5), the revised phase angle $\alpha_p$ of the fundamental voltage vector is found and used to decide the switching time.

$$\alpha_p = \begin{cases} 0, & 0 \le \alpha < \alpha_h \cdots\cdots Area1 \\ \frac{\alpha - \alpha_h}{\frac{\pi}{6} - \alpha_h} \frac{\pi}{6}, & \alpha_h \le \alpha < \frac{\pi}{3} - \alpha_h \cdots Area2 \\ \frac{\pi}{3}, & \frac{\pi}{3} - \alpha_h \le \alpha \le \frac{\pi}{3} \cdots Area3 \end{cases} \tag{5}$$

Here, $\alpha$ is the phase angle of the referance voltage vector.

## 3.2 Synchronous Overmodulation PWM Method with Low Frequency

Generally, for asynchronous PWM, an error in the output voltage of $V_{dc} \times F_{inv} \times T_{samp}$ for the offset voltage and $2\pi \times F_{inv} \times T_{samp}$ for the phase can occur. When the switching frequency is low, the load system becomes unstable due to situation of above. Therefore, for the propulsion control system of railroad vehicles with a switching frequency limited to a couple hundred Hz, a synchronous method is required. A PWM method which can most simply materialize low frequency switching from a stable overmodulation algorithm taken from a space voltage vector of a whole course is described.

First, the sampling time $T_{samp}$ for the PWM control of the synchronous control of the fundamental frequency is shown in equation (6) and is recalculated with the inverter control frequency $F_{inv}$ and modulation number $N_m$.

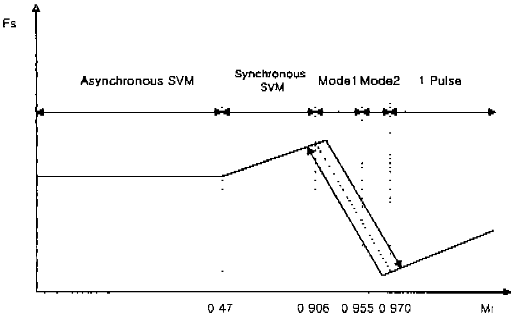


Fig. 5 PWM pattern(switching frequency) by proposed method.

$$T_{samp} = \frac{1}{2 \cdot F_{inv} \cdot N_m} \tag{6}$$

Here, the modulation number which decides the switching frequency must satisfy the $3 \times N$ conditionand $N$ must also be an odd number. This is because it must satisfy the 1/4 symmetry. In case it does not, the overmodulation mode, in which the switching number becomes smaller, has an increase in harmonics. As the switching changes into the base frequency of the 6 step, a $2\pi \times F_{inv} \times T_{samp}$ phase instantaneous delay occurs, causing a transient component build up in the motor current. As long as the condition above is satisfied, due to the synchronous space vector method, a low harmonic component without a separate function will result in a superior continuous control up until the 6 step. In the area where the inverter frequency is low, the asynchronous space vector modulation method is used. When the modulation number reaches around 9, there is a change to the synchronous mode. The change into the synchronous mode is when the modulation number of the asynchronous mode is greater than 9 and the phase is 0 or $\pi$, $\pi$ or $2\pi$. The sampling time is then recalculated to make it synchronous.

Fig. 5 shows the proposed method controlling the output voltage up until the 6 step. For the switching frequency, the modulation number $N_m$ is set as 9 and is controlled within 500Hz. When it is asynchronous, it is constantly set at 380Hz. This type of switching method not only optimize the designed controllable switching frequency, uses a single control function to minimize harmonics, eliminates switching gear phenomenon, and has constant control over the output, but is also simply programmable. During a real time programming, (2), (3), and (4) turn out to be too complicated. Therefore, a 3rd function using the least square method for the referance voltage and holding angle about $M_i$ was found to form the approximation equations (7) and (8).

$$V_c^* = V_{dc} \cdot [1000 \cdot (0.6094\ M_i^3 - 1.7153\ M_i^2 + 1.6106\ M_i + 0.5039) - 1007.742] \tag{7}$$

$$\alpha_h = 10000 \cdot (0.7966\ M_i^3 - 2.3190\ M_i^2 + 2.2508\ M_i - 0.7284) + 0.5312 \tag{8}$$

Fig. 6 shows the results from a simulation of applying the proposed method to a railroad vehicle's acceleration or deceleration characteristics. A superb control without transient components in the input/output current is seen and when compared with the characteristics of the conventional method in Fig. 4, the usefulness and practical capabilities can also be seen.

Fig. 7 depicts the comparison of the harmonics contained in the output current about the normal frequency of the conventional and proposed methods with the PWM control up until the 6 step. The conventional method can not maximize the use of the switching, because of limitation of PWM generation by pattern at synchronous mode pattern. The proposed method reduces the harmonics component during the overall 6 step. Therefore, the proposed method can increase efficiency of the system by decreasing the size of the input/output filter of the propulsion control system.

Introduced above is a low frequency synchronous overmodulation method for an improvement in the total performance of the propulsion control systems for railroad vehicles. Compared to the conventional method, a harmonics quanity of frequency bandwith was decreased and the continuous acceleration or deceleration control characteristics until the 6 step were tremendously improved. These characteristics were then tested with an experiment using a practical size model.

## 4. Experiment Results

The low frequency synchronous space vector modulation method proposed above was tested through application with the PWM method of the propulsion control system of a railroad vehicle. The experimental system used is portrayed in Fig. 8.

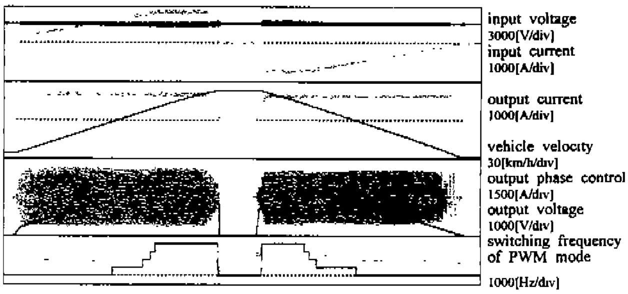


Fig. 6. Continuos current control performance by proposed PWM method.

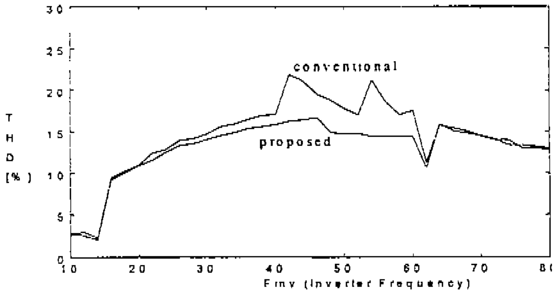


Fig. 7. THD comparison between conventional method and proposed method.

A IGBT model VVVF inverter of a 1.65MVA level and four 200kW traction motors are in a parallel connection and an equivalent inertial mass of a 160ton raiload vehicles was used. It also uses a 32bit DSP as the main control device. The experiment uses the same conditions as a operating railroad vehicle. The experiment consisted of accelerating until 85km/h and coasting for a set period of time and then regenerative braking was applied at 75km/h. For the PWM operating conditions, the asynchronous switching frequency starts at 380Hz and when synchronous, the modulation number was set at 9, keeping it under 500Hz. The system disturbance due to the cramped PWM width was restrained and for using this one even in the case of a GTO element, the minimal on/off time was set at 100us to verify the validity of the application. Fig. 9 depicts the characteristics of current of mode change during continuous control until the 6 step. It can be seen to proceed excellently without any transient state. The harmonics in the current are also superior to that of the conventional method. Fig. 10 and 11 each show continuous voltage and current control. It can be seen that not only a smooth output control when acceleration or deceleration occurs, but that there are no transient conditions from the mode procedure.

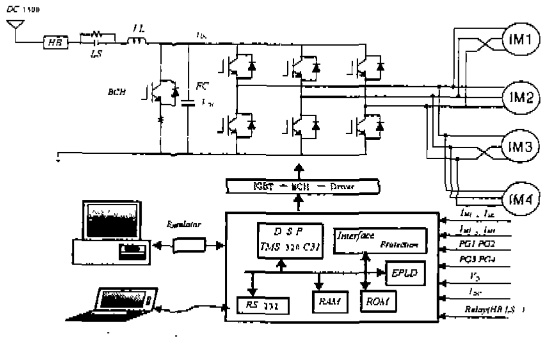
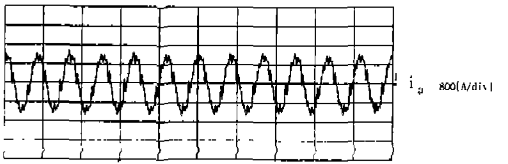
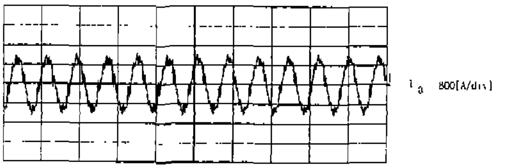


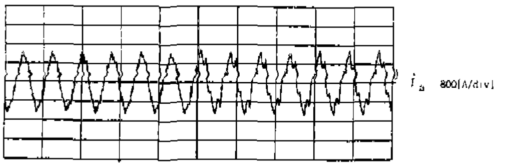
Fig. 8. Configuration of experimental set-up.



(a) synchronous mode --> overmodulation mode 1 procedure characteristics



(b) overmodulation mode 1 --> overmodulation mode 2 procedure characteristics



(c) overmodulation mode 2 --> 1 pulse mode procedure characteristics

Fig. 9. Current waveform for PWM mode change.

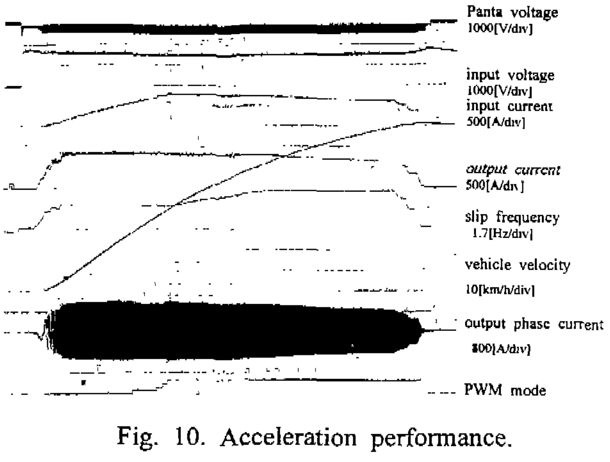


Fig. 10. Acceleration performance.

The proposed PWM method can form an optimal design of the propulsion control system and improve the application of the tractive effort control method in railroad vehicles.

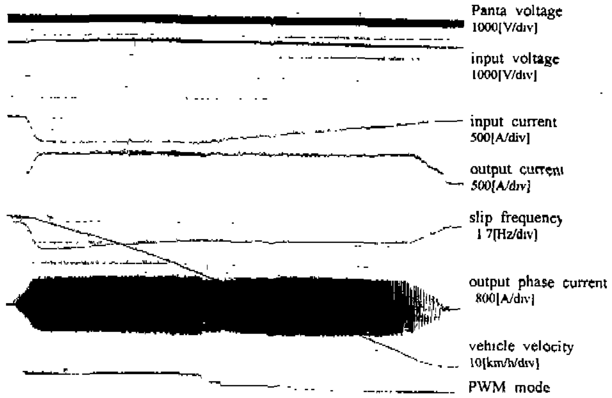


Fig. 11. Regeneration performance.

## 5. Conclusion

This paper proposed a improved PWM method in order to accomplish regulated tractive effort control characteristics of the propulsion control system in railroad vehicles. The possibility was proved through simulation and an experiment using a 1.65MVA level propulsion control system which is the actual applied system and an equivalent inertial mass of 160ton raiload vehicles which verified the superb characteristics and usefulness. The proposed method uses the actual applied Swiching frequency range of 500Hz for the continuous voltage control until the 6 step and decreased the harmonic component. This should result in the use of this optimal design propulsion control system and improved tractive effort control method in future subways, trains, and magnetic levitation trains.

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