Optimal pulse width modulation for permanent magnet synchronous motor drive with improved torque and thermal losses using pulse numbers

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Abstract. This paper utilises the concept of pulse numbers to provide a new optimal pulse width modulation strategy for permanent magnet synchronous motor operation. The benefits of traditional modulation systems are preserved, as is an improvement in torque and thermal loss reduction. The continuous modulation approaches' performance limitations are solved by separating the performance constraints based on the drives surface area. The rotating component, which is regulated through odd and even pulse numbers, is used to mimic torque and thermal losses. With increases to 20 rpm and 30 rpm speeds, the suggested methods boost the 6% to 8% line current. Thermal losses are reduced by 21°C to 23°C, and torque is improved by 2 to 4 Nm. The proposed system is implemented by creating a MATLAB model that ensures the theoretic concept.

Keywords: AC drives, Torque losses, Temperature variation, Permanent magnet drive, PWM

1. Introduction
Many Pulse Width Modulation (PWM) techniques are proposed for improving the torque losses and thermal performance of Permanent Magnet Synchronous Motor (PMSM) drives. The estimation of torque losses predicted from flux is incorporated into PWM [1]. This simple current control technique indirectly increases the current ripple in the high torque region. Sine PWM sampling for control of the torque speed control, including the filtering process [2]. Hardware availability limits this frequency conversion control strategy. Flux-oriented hardware configurations were studied [3] for reducing torque ripples. This analysis covers the impact on starting and running conditions and thereby initiates the motivation for this work. A Finite element simulation was done to optimise the torque ripple under no load conditions [4]. The developed electromotive force neglects the impact of load variations for a wide range of permanent magnet designs. Electric vehicle related research matches with torque loss in the driving conditions examined in [5]. Efficiency distribution through the analysis seems uneven for various load conditions. The structural characteristics of the motor designed to improve the torque loss are modelled [6]. The built-in modification enhances the efficiency compromise with control. There is a relationship between motor design and torque control based on numerical values [7]. Magnet size directly influences the PWM control parameter derived for torque specifications. Furthermore, this control supports fault identification and maintenance [8]. The analysis validates the proposed concept to improve thermal losses. The same optimization objective for reducing these losses through current
density has been developed [9]. Improvement in the loss reduction of around 50% is achieved with conceding the load conditions.

A nonlinear controller considers the finite duration of chaos control [10]. Many of the system parameters disobey this nonlinear control. [11] is a compensation scheme for balancing the PMSM drive's high speed and peak voltage. This drooping control method reduces the torque and thermal losses for a specific range of load angles. Moreover, the air gap magnetic flux improves the load angle, thereby reducing the losses [12]. Analytical equations developed for magnetic flux are difficult to implement with PWM. A new vector control scheme combines the advantages of magnetic flux load angle schemes with PWM methods [13]. These schemes balance torque and thermal losses at discrete intervals. [14] investigates a Fuzzy-based PID controller for associating a sudden load change. Although this control scheme improves the system response, it does not show in the losses. Periodic injection of harmonics to improve the mechanical characteristics fails to compensate for the losses [15]. This report shows that the aperiodic method of harmonic injection directly influences the torque and thermal losses. An optimization technique proposed in [9] enhanced with the statistical variance method at low speed is presented [16]. An initial study shows that the impact of thermal and torque losses has a positive impact on the environment. This indicates that the proposed work is important in technical and commercial aspects. These advantages are extracted, and the modelling of torque and thermal losses is done based on the revolving component, which is controlled through odd and even pulse numbers.

2. Modelling torque and thermal losses of permanent magnet synchronous motor drive

The modelling of Torque and Thermal losses of PMSM drive are developed from machine energy transfer model which is discussed in many literatures. In this section, the existing model adapted for implementing the optimal PWM techniques is discussed.

2.1 Modelling of permanent magnet synchronous motor torque

The generalized model of Torque produced by PMSM drive is given as

\[
T = \frac{3P}{2} \left( (Li + \lambda)^T i + i^T \frac{d\lambda}{dt} \right)
\]  

(1)

From formula 1, the torque generated from the drive depends on phase inductance and flux linkage varied from the phase current.

![Figure 1. Analytical solution of PMSM drive boundaries between Surface area vs Torque vs Temperature variation](image.png)
The term $d\lambda/dt$ gives the idea about controlling the torque in an effective manner. Commonly, the rotating component analysed as single complex quantity and represented in terms of all three phases is presented as

$$T = \sum_{n \text{ odd}} T_{\text{peak}} \cos(n\theta - \phi_{\text{abc}})$$  \hspace{1cm} (2)

Formula 2 signifies that Torque composed of individual Torque peak values which are govern by odd harmonics which is existing for each phase and their phase difference. Revolving component $n\theta$ can be controlled from optimal PWM techniques which is decided from the switch operating periods.

2.2 Permanent magnet synchronous motor Thermal Model

Temperature variation at running condition measured from the surface quantity of PMSM and initial ambient temperature which is always consider as minimum values is offered in formula 3 as

$$\frac{\partial T_c}{\partial S} = \frac{h}{k} (T_c(S) - T_{\text{min}})$$  \hspace{1cm} (3)

Thermal convection conductivity ratio $h/k$ is constant for entire analysis. Additionally, the relationship between revolving component and temperature loss is given in formula 4 as

$$T_{c(\text{Loss})} = \sum_{n \text{ odd}} (T_c(\lambda(n\theta)) - \lambda(n\theta) f(T_c))$$  \hspace{1cm} (4)

can be controlled from optimal PWM techniques which is decided from the switch operating periods.

2.3 Analytical Solution for balancing permanent magnet synchronous motor torque and temperature

To develop an optimal analytical solution for PMSM drive balancing between Torque and Thermal model is the primary step in terms of formula 1 to 4. The analytical solution is mapped for identifying the boundary of each parameter and presented in Figure 1. It is inferred that the analytical solution not continuous and the impact of losses are varied block by block in a small range. Hence the conventional PWM schemes applied for entire operating frequency which is not suitable and need to operate optimum manner discussed in next section.

3. Proposed optimal pulse width modulation using pulse numbers

The limitations of conventional continuous PWM techniques determined based on the Torque and Thermal model of PMSM is discussed. Modification done in revolving component from the boundary edges of each PMSM construction features. Later the classification of optimum PWM based on the pulse number is discussed in this section. The gating pulses produced from the Conventional Continuous PWM applied to leg of PMSM inverter drive and the current flow in the drive in relate with flux linkage is presented in formula 5, formula 6 and formula 7 as

$$V_n = \sum_{n \text{ odd}} (T_c f(\lambda(n\theta)) - \lambda(n\theta) f(T_c))$$  \hspace{1cm} (5)

$$I_n = \sum_{n \text{ odd}} \frac{V_n}{n\omega L}$$  \hspace{1cm} (6)

$$\lambda_n = \sum_{n \text{ odd}} \frac{V_n}{n\omega}$$  \hspace{1cm} (7)
These formula shows that the PWM generation depends on the revolving component $n\theta$ as mentioned in formula 2. If this component is continuous failed to match out the analytical calculation discussed in the previous section. Hence the modification needs to do in this rotating component with optimal operating duration. To develop an optimal PWM same as the operation of continuous but the revolving component must be equivalent average of previous and next harmonic content of voltage in formula 8 with formula 9 and current which is given as

$$V_n = \sum_{n=\text{odd}} \left( \frac{V_{n-1} + V_{n+1}}{2} \right)$$

(or)

$$V_n = \sum_{n=\text{odd}} \left( \frac{V_{n-2} + V_{n+2}}{2} \right)$$

which can be implemented in formula 6 and formula 7 reflected as torque equation derived from formula 2 turn into formula 10 as

$$T_{\text{optimal}} = T_{\text{peak}} \sum_{n=\text{odd}} \left( \cos((n\theta - \phi_{abc}) + \cos((n+1)\theta - \phi_{abc}) \right)$$

Similarly, the temperature variation in formula 11, from previous harmonic content given as

$$T_{c_{\text{optimal(Loss)}}} = \sum_{n=\text{odd}} \left( T_c f (\lambda((n-1)\theta)) - \lambda((n+1)\theta) f (T_c) \right)$$

the temperature variation in formula 12, from next harmonic content given as

$$T_{c_{\text{optimal(Loss)}}} = \sum_{n=\text{odd}} \left( T_c f (\lambda((n+1)\theta)) - \lambda((n-1)\theta) f (T_c) \right)$$

The optimal PWM developed with constraints identified and implemented with formula 5 to formula 10.

4. Validation of optimal proposed pulse width modulation

Table 1 shows the proposed optimal PWM that was implemented in the system specification. From formula 5 to formula 10, a PMSM model was constructed in the MATLAB / Simulink environment using continuous and discontinuous PWM coding. Figure 2. (a)–(c) The gating pulses applied to the PMSM drive inverter leg with 1/10th of the fundamental value using traditional PWM are compared to the suggested optimal PWM for odd and even pulse numbers.

| Specification       | Values |
|---------------------|--------|
| Supply Voltage      | 48 V   |
| Battery Capacity    | 7000 Ah|
| Speed               | 500 rpm|
| Power               | 4.8 kW |
| Specification | Values |
|---------------|--------|
| Current       | 100 A  |
| Connection    | Star   |

**Figure 2.** Comparison of Gating Pulses to Leg 1 switches for (a) Conventional PWM with regular pulse number (b) Proposed optimal PWM with odd pulse number (c) Proposed optimal PWM with even pulse number

**Figure 3.** Comparison of PMSM Three phase currents for (a) Conventional PWM with regular pulse number (b) Proposed optimal PWM with odd pulse number (c) Proposed optimal PWM with even pulse number
Figure 4. Comparison of Speed variation for Conventional PWM with Proposed optimal PWMs

Proposed optimal PWM for odd number of 5 pulses and even number of 6 pulses with total of 50 and 60 pulses for fundamental period. After implementation of these pulses, the line current is measured and plotted in Figure 3. (a) – (c). Comparing with conventional PWM, the proposed optimal PWM methods odd and even pulses improved the current by 8 % and 6 % respectively. This is clearly studied from the simulated results without affecting the existing performance.

Table 2. Comparison of PMSM drive parameters for proposed optimal PWM scheme with conventional PWM

| Parameters      | Ideal PWM | Torque Control | Proposed Optimal PWM |
|-----------------|-----------|----------------|----------------------|
|                 | PWM [1], [2], [7],[13] | Design [3], [6], [11], [15] | Odd Pulse Number | Even Pulse Number |
| No of Pulses    | N         | 3N             | 3N+1                | 2N−1              | 2 N              |
| Line Current    | 100 %     | 100 − 2.2 %    | 100 − 0.4 %         | 100 + 8.1 %       | 100 + 6.3 %     |
| Speed           | 100 %     | 100 + 1.3 %    | 100 + 3.2 %         | 100 + 4.7 %       | 100 + 6.2 %     |
| Torque          | 100 %     | 100 + 0.2 %    | 100 − 0.5 %         | 100 + 2.3 %       | 100 + 2.3 %     |
| Temperature     | 100 %     | 100 − 0.5 %    | 100 + 0.14 %        | 100 + 4.2 %       | 100 + 6.2 %     |
| Torque Loss     | 100 %     | 100 − 2.5 %    | 100 − 0.5 %         | 100 − 0.5 %       | 100 − 1.1 %     |

Figure 4. demonstrated the speed performance of conventional PWM in compete with proposed optimal PWM for odd and even pulse numbers. The proposed odd and even pulses optimal PWM methods upgraded the speed result of 20 rpm and 30 rpm respectively. Temperature variation of conventional PWM in assess with proposed optimal PWM for odd and even pulse numbers is offered in Figure 5.
Figure 5. Comparison of Temperature variation for Conventional PWM with Proposed optimal PWMs at running Condition

Associating conventional PWM with the proposed optimal PWM methods odd and even pulses reduce the temperature rise in the range of 21° C to 23° C. Figure 6, exhibited the torque performance of conventional PWM in competing with the proposed optimal PWM for odd and even pulse numbers. When compared to conventional methods, the proposed optimal PWM method increased full-load torque by 2 to 4 Nm.

Figure 6. Comparison of PMSM Torque for Conventional PWM with Proposed optimal PWMs

The torque loss is in shape with conventional PWM, but the loss is reduced by 0.5 to 1.5% of the proposed optimal PWM, which is presented in Figure 7. Summary of improvement after implementing the optimal PWM is tabulated in Table 2.
Figure 7. Comparison of PMSM Torque loss for Conventional PWM with Proposed optimal PWDs

5. Conclusion
An analytical solution of an effective PWM switching technique is proposed for extracting the advantages of typical PWM schemes utilised for PMSM drive. The analytical solution considers the drive surface area and torque variation as a function of operating temperature. From the previous and next harmonic profiles, the revolving component split into two discontinuous components. According to the study, the new PWM procedures ensure performance increases of 20 and 30 rpm speeds, 6 to 8% line current, and 2 to 4 Nm of torque. With these optimal systems, real-time disturbance can be introduced in the future.

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