Overmodulation and Six-Step Operation of IPMSMs under Current Vector Control

By

Youssef Elsaid Abdallah

Submitted to the Department of Electrical Engineering, Electronics,
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Author…………………………………………………………………………...
Youssef Elsaid Abdallah

Certified by……………..………………………………………………………….
Hadi El Khatib
Dr.-Ing
Thesis Supervisor

Certified by……………..………………………………………………………….
Aitor Vázquez
Associate Professor
Thesis Supervisor

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Abstract

The motivation behind this work is to optimize electric motor control by extending the operation from the linear region through Overmodulation (OVM) up to six-step operation under the industry standard Current Vector Control (CVC) to optimize the DC-link voltage utilization and consequently increase the power output and overall efficiency of traction motors in electric vehicle applications. Achieving this under CVC is quite challenging due to the increase in the harmonic distortion beyond the linear limit through the OVM region which reaches the maximum value at six-step operation, this makes motor control very challenging under CVC which is originally designed for linear operation (dc quantities). The first step is to review the state-of-the-art knowledge in PMSM drives, OVM techniques, modulation regions (Linear, OVM I, OVM II, six-step operation), CVC control variations and related issues and, lastly, the most famous attempts in the literature to achieve OVM and six-step operation of PMSM drives under CVC have been reviewed. The second step is to analyze and compare between some OVM techniques in open-loop and propose some enhancements to optimize the performance before integration into the proposed closed-loop control structure. Next step, the third one, is to develop the control subsystems for the proposed closed loop structure in SIMULINK environment (e.g., MTPA/Flux weakening, current controller, anti-windup scheme, OVM saturation blocks, transition scheme between modulation regions, IPM machine model) and to integrate them in a way to a achieve a continuous, seamless transition between the modulation regions with no abrupt changes or discontinuities with good torque tracking accuracy. The entire modulation region is covered by a dual-mode OVM strategy that utilizes a modified scheme for the MPE and Holtz OVM algorithms and a methodology for the transition in between the two algorithms. The fourth step is to address the discrete time problem in six-step operation and to propose a solution to the problem of subharmonics in torque and currents. The final step involves the validation of the proposed control structure through closed-loop simulations and analysis of the results including transition, torque accuracy and a detailed evaluation of the effectiveness of the implemented method to solve the discrete-time issue in six-step operation. In the end, a continuous, stable, and seamless transition between all modulation regions has been achieved with an excellent torque tracking accuracy in the entire modulation region in simulation in

SIMULINK. For future work, it’s required to validate the proposed structure on a real test bench with proper discrete-time model that includes current sampling and processing, PWM-Insertion, delay compensation, and with a fine tuning of the CVC variables such as bandwidth, active damping coefficient, anti-windup gain calibration and other parameters.

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Please note that the contents of this master’s thesis are subject to an NDA with Mercedes-Benz AG and thus is not available for public access.

Chapter One

1. Introduction

1.1 Background

In recent years, there has been a spike in the demand for highly efficient and high-performance electric motor control systems in industrial and consumer applications. Electric motors are the powerhouses of modern industry, they are an integral part of a wide range of applications ranging from household appliances to electric and hybrid vehicles. These applications are becoming more advanced, which lead to the need for motor control algorithms that can optimize performance, efficiency, and reliability.

One of the main challenges in motor control is the efficient utilization of the inverter's DC-link voltage, the level of utilization directly influences the motor output torque and speed capabilities. Conventional linear modulation techniques like Sinusoidal Pulse Width Modulation (SPWM) present an easy and straightforward approach for motor control by maintaining a linear relationship between the control signal and the output voltage. However, such linear methods limit the utilization of the inverter's DC-link voltage, which could lead to suboptimal performance depending on the operating conditions.

To address these limitations, overmodulation OVM strategies have evolved, extending the modulation from the linear range through overmodulation and, ultimately to six-step operation. OVM strategies extend the modulation index beyond the linear range, which allows the motor to make use of a higher voltage percentage from the DC-link without physically increasing the DC-link voltage. Six-step operation represents the maximum possible DC-link voltage utilization, where the transistors of the inverter legs are switched in a predefined pattern, this also minimizes the switching losses. However, maintaining a stable operation in the OVM region is quite challenging since the harmonic distortion starts to increase significantly beyond the linear limit and reaches the maximum value at six-step operation, this makes motor control very challenging under Current Vector Control (CVC) which is originally designed for linear operation (dc quantities).

Consequently, the transition from linear modulation through OVM to six-step represents a continuum of smart control strategies that can balance the trade-offs between harmonic distortion, torque ripple and inverter DC-link voltage utilization. The understanding and optimization of OVM strategies is crucial for enhancing motor efficiency and performance, especially in electric vehicles where the motor is required to operate in a wide range of speeds and load conditions. This thesis addresses the operation of electric motor under OVM and six-step operation and proposes a control structure that can operate in the entire modulation region with a continuous, seamless transition from linear through OVM up to six-step operation with a focus on the steady state performance, the undertaken topology is CVC.

1.2 Objectives

The central theme of this thesis is to optimize electric vehicle traction motor control by extending the operation from linear modulation through OVM and up to six-step operation under CVC, a task which is quite challenging due to the increase in the harmonic distortion in the OVM operation where the maximum harmonic distortion occurs at six-step operation. This makes the operation in such conditions under the industry standard CVC quite cumbersome since CVC is originally designed for linear operation (dc quantities). The overall objectives of this work can be listed as follows:

- Presenting a thorough review of the state-of-the art OVM techniques.
- Open loop analysis of the most common OVM techniques and comparing between them to choose which ones to use in the proposed structure.
- Integration of the chosen OVM techniques through some modifications in the closed loop structure to achieve a continuous, seamless transition between linear, OVM I, OVM II and six-step operation with a stable operation and an excellent torque tracking accuracy.
- Simulation and validation of the proposed structure in MATLAB/SIMULINK.
- Identification of the shortcomings of the proposed structure.
- Future work suggestions.

Chapter Two

2. Conclusion and Future Work

2.1. Conclusion

The control of a traction motor in an electric vehicle under the industry standard CVC is quite a cumbersome task when the motor is required to operate in OVM and six-step modulation. This is due to the increase in harmonic distortion in OVM that reaches its maximum value in six-step operation, however, the conventional CVC is originally designed for linear operation, where the current reference is dc and the phase voltage is sinusoidal, however, in OVM, the circular voltage command is saturated on the hexagonal voltage boundary limit and this leads to the distortion of the sinusoidal voltage waveform and thus the introduction of harmonics in the current, which are thus fed back to the current controller. This interaction makes the implementation difficult and requires fine calibration to work in reality. Nevertheless, OVM is very beneficial for traction drives since it enhances the utilization of the DC-link voltage without physically increasing the DC-link voltage, this enhances the efficiency and performance of the electric motor without any extra cost investment.

This thesis has proposed a control structure using CVC that allows a stable operation of the motor in the entire modulation region: from linear through OVM and up to six-step operation. The entire proposed control structure has been validated in MATLAB/SIMULINK and the most important results have been documented in this work. The proposed structure mainly utilizes the complex vector current control structure along with the tracking anti-windup scheme. The entire modulation region is covered by a dual-mode OVM strategy that utilizes a modified scheme for the MPE and Holtz OVM algorithms and a methodology for the transition in between the two algorithms. A continuous and seamless transition between the modulation regions without any gaps or abrupt changes has been achieved with an excellent torque tracking accuracy in the entire modulation region. This has been done through employing the state-of-art CVC knowledge, combining, and modifying the MPE algorithm and Holtz algorithm in a novel way to achieve the previously stated operation requirements. The discrete time issue in six-step operation, which leads to undesired subharmonics in the currents and torque, has been thoroughly addressed and a simplified PWM insertion solution using MPE algorithm was implemented as a partial solution to the problem. The short comings of the proposed structure in six-step operation have been directly addressed. Nevertheless, if the micro-controller sampling rate is very high, the discrete time issue is no longer evident in the proposed structure, however, operating the micro-controller at very high sampling rates would increase the computational power requirements and would consequently increase the cost of the micro-controller. Future work is needed to completely fix the discrete-time issue and fully eliminate the subharmonics in currents and torque at standard moderate sampling rates.

2.2. Future Work

The working solution in simulation in SIMULINK will be validated on a high-performance electric drive system with a more detailed implementation of the discrete-time model that includes current sampling, processing, PWM-Insertion and with a fine tuning of the CVC variables such as bandwidth, active damping coefficient, anti-windup gain calibration and other parameters. An assessment of the voltage utilization will be carried out using oscilloscope measurements. The torque, DC-current ripple and torque dynamics will be analyzed in the complete OVM region.