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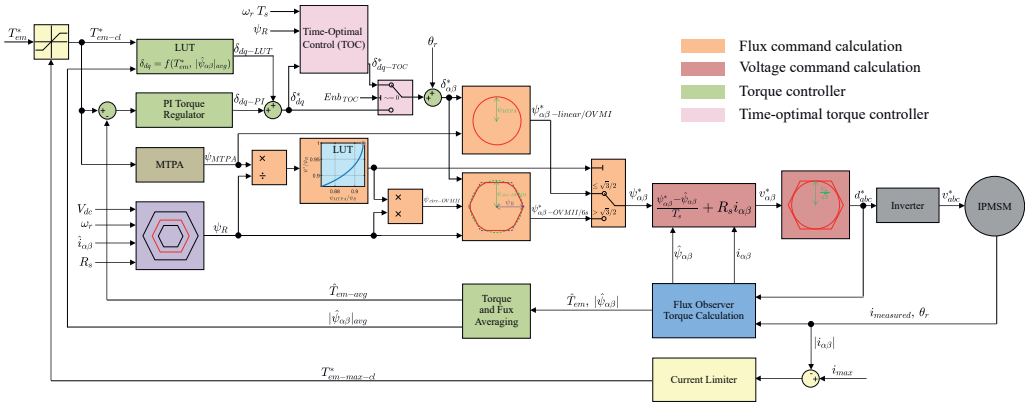
Hrsg.: Prof. Dr.-Ing. Dieter Gerling

Hadi El Khatib

# Deadbeat Flux and Torque Control in the Linear, Overmodulation, and Six-Step Regions for Automotive Traction Applications

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# Deadbeat Flux and Torque Control in the Linear, Overmodulation, and Six-Step Regions for Automotive Traction Applications

**Hadi El Khatib**

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# Abstract

Six-step modulation offers notable advantages over the conventional Space Vector Pulse Width Modulation (SVPWM) in the flux-weakening region. It enhances the torque capability of the machine and guarantees maximum power performance by maximizing battery voltage utilization, a critical component of electric cars due to its high cost. Moreover, the system's efficiency is enhanced by reducing the phase current required for flux weakening and minimizing switching losses. Conversely, under identical operational requirements, it becomes feasible to downsize the battery capacity and/or machine/inverter ratings, leading to cost, weight, and space savings.

This thesis introduces an enhanced Deadbeat Flux Vector Controller (DBFC) as a one single control law capable of operating interior permanent magnet synchronous machines (IPMSMs) across the entire torque-speed range. Stable operation in the full voltage modulation range, including SVPWM, overmodulation (I and II), and six-step, is achieved through precise tracking of various flux trajectories. DBFC enables a continuous and seamless transition between the different operating regions, with the modulation index varying linearly with speed in the constant torque region. With this proposed strategy, undesirable torque dynamics, stability problems, and increased computational efforts, associated with using multiple control laws are completely avoided.

A comprehensive analysis of DBFC's transient performance at the maximum voltage limit (six-step) is conducted. A time-optimal torque control algorithm is developed to achieve the fastest possible torque response, significantly reducing the settling time, particularly when operating at the voltage limit (six-step). The torque can be controlled with high accuracy and high robustness to machine parameter variations. DBFC allows for the control of the instantaneous flux vector, encompassing both steady-state and transient flux trajectories, without requiring trade-offs between steady-state six-step behavior and excellent transient performance. The proposed controller offers significant advantages over conventional Field-Oriented Control (FOC) and it is simpler to implement.

If operation in overmodulation, including six-step, is not desirable based on the application and requirements, another variant of the classical Direct Torque Controller (DTC) can be employed. The operation of the Deadbeat-Direct Torque and Flux Controller (DB-DTFC) is extended to the second flux weakening region by the Square-Root Condition (SRC), ensuring robust and reliable maximum-torque-per-flux (MTPF) operation with a circular flux trajectory. A robust Gopinath flux linkage observer is implemented and evaluated since the flux is a controlled variable for both DBFC and DB-DTFC.

Simulation and experimental results are provided to validate the proposed control strategies, which have been implemented on an automotive microcontroller with a high-power, high-performance automotive traction machine.

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# Nomenclature

## Symbols

| | | |
|---|---|---|
| $v$ | Stator voltage | $[V]$ |
| $i$ | Stator current | $[A]$ |
| $\psi$ | Flux linkage | $[Vs]$ |
| $T_{em}$ | Electromagnetic torque | $[Nm]$ |
| $\omega_{rm}$ | Mechanical angular speed of the rotor | $[rad/s]$ |
| $\omega_r$ | Electrical angular speed of the rotor | $[rad/s]$ |
| $n_{rm}$ | Mechanical angular speed of the rotor (revolutions per minute) | $[min^{-1}]$ |
| $L$ | Inductance | $[H]$ |
| $\psi_{pm}$ | Permanent-magnet flux linkage | $[Vs]$ |
| $R_s$ | Stator resistance | $[\Omega]$ |
| $R_i$ | Iron-loss resistance | $[\Omega]$ |
| $P$ | Number of poles | |
| $V_{dc}$ | Dc-link voltage | $[V]$ |
| $I_{dc}$ | Dc-link current | $[A]$ |
| $\psi_R$ | Circumradius of the flux hexagon | $[Vs]$ |
| $MI$ | Modulation index | |
| $R_\psi$ | Average flux magnitude normalized to $\psi_R$ | |
| $V_1$ | Peak magnitude of the fundamental phase voltage | $[V]$ |
| $f_1$ | Fundamental electrical frequency | $[Hz]$ |
| $f_s$ | Switching frequency | $[Hz]$ |
| $N_p$ | Pulse number | |
| $\theta$ | Angle referred to the $\alpha - axis$ | $[rad]$ |
| $\delta$ | Angle referred to the $d - axis$ | $[rad]$ |
| $\theta_r$ | Rotor position | $[rad]$ |
| $t$ | Time (continuous) | $[s]$ |
| $T_s$ | Sampling time | $[s]$ |
| $k$ | Current sample (discrete) | |

| | | |
|---|---|---|
| $K_p$, $K_i$ | Coefficients of the proportional and integral terms | |
| $S_{a,b,c}$ | Switching states of the three-phase voltage source inverter | |
| $\Delta T_{em}$ | Change in the electromagnetic torque | $[Nm]$ |
| $M$ | Slope of the differential torque line | |
| $B$ | q-intercept of the differential torque line | $[Vs]$ |
| $-x$, $-y$ | Flux circle center coordinates | $[Vs]$ |
| $n_{opt}$ | Optimal number of time steps to achieve TOC | |
| $P_{cu}$ | Copper losses | $[W]$ |
| $P_i$ | Iron losses | $[W]$ |
| $f_{abc}$ | Stationary three-phase reference frame | |
| $f_{\alpha\beta}$ | Stationary two-phase reference frame | |
| $f_{dq}$ | Synchronous two-phase reference frame | |
| $j$ | Unit imaginary number | |
| $\textcircled{x}$ | Operating point ($x \in \mathbb{N}^*$) | |
| $\hat{x}$ | Estimated parameter | |
| $x^*$ | Commanded variable | |

# Acronyms and Abbreviations

| | |
|---|---|
| AC | Alternating current |
| CM | Current model |
| CO | Current observer |
| CVC | Current vector control |
| DB-DTFC | Deadbeat-direct torque and flux control |
| DBFC | Deadbeat flux vector control |
| DC | Direct current |
| DSC | Direct self control |
| DTC | Direct torque control |
| EV | Electric vehicle |
| FO | Flux observer |
| FW | Flux weakening |
| HIL | Hardware in the loop |
| IGBT | Insulated-gate bipolar transistor |
| IPMSM | Interior permanent magnet synchronous machine |
| LPF | Low-pass filter |
| LUT | Lookup table |
| MOSFET | Metal–oxide–semiconductor field-effect transistor |

| | |
|---|---|
| MTPA | Maximum torque per ampere |
| MTPF/V | Maximum torque per flux/voltage |
| MTPL | Maximum torque per loss |
| OPP | Optimized pulse pattern |
| OVM | Overmodulation |
| PI | Proportional–integral controller |
| PWM | Pulse width modulation |
| RMS | Root mean square |
| SRC | Square root condition |
| SVM | Space vector modulation |
| TOC | Time optimal control |
| VATC | Voltage angle torque control |
| VM | Voltage model |