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Model Predictive Control for Electric Drive Systems

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ABSTRACT: Model Predictive Control (MPC) has emerged as an influential control strategy for electric drive systems, offering enhanced dynamic performance, constraint handling, and multi-objective optimization capabilities. Unlike traditional techniques such as Field-Oriented Control (FOC) or Direct Torque Control (DTC), MPC optimizes control actions by predicting future behavior over a horizon and minimizing a cost function. Pre-2018 implementations—including Finite-Control-Set MPC (FCS-MPC) and Continuous-Time MPC (CT-MPC)—address torque, flux, and current regulation directly via voltage vector selection, offering rapid responses and reduced ripple. Key advancements include torque control with minimized ripple in Induction Machines ([IET, 2015]), low switching frequency MPCC for Permanent Magnet Synchronous Motors (PM-SMs), and sensorless predictive torque control of Induction Machines (IMs) encompassing reactive power regulation ([2018 thesis]). Challenges remain in computational demand, cost weighting factor tuning, and system model fidelity. Comparative studies underline MPC's ability to manage converter constraints and nonlinearities more intuitively compared to PWM-based FOC. This paper reviews foundational MPC formulations in drive applications up to 2017, analyzes experimental achievements, and synthesizes trade-offs in performance, implementation complexity, and robustness. In conclusion, we outline future directions such as reduced-complexity algorithms, explicit MPC, and multi-phase drive extensions.

KEYWORDS: Model predictive control; electric drives; finite-control-set MPC; predictive current control; induction motor; torque ripple; PM-synchronous motor; predictive torque control; sensorless drive.

I. INTRODUCTION

Electric drives—for induction motors (IMs) and permanent magnet synchronous motors (PMSMs)—are core to industrial and automotive applications. Conventional control strategies such as Field-Oriented Control (FOC) and Direct Torque Control (DTC) rely on cascaded loops and PWM synthesis. In contrast, Model Predictive Control (MPC) offers a compelling alternative by optimizing future control moves based on a system model and explicit cost minimization while accommodating system constraints.

Predating 2018, MPC approaches for electric drives commonly split into **Finite-Control-Set MPC (FCS-MPC)**—which directly selects inverter voltage vectors from a finite set—and **Continuous-Time MPC (CT-MPC)** variants solving analytic predictive control laws. FCS-MPC enables direct torque and flux control with fast dynamic response, whereas CT-MPC introduces state-feedback laws that can decouple disturbance effects.

Numerous studies explored MPC for IM and PMSM drives, focusing on torque ripple reduction, switching frequency moderation, and sensorless implementations. Pre-2018 works include IET's model predictive torque control targeting reduced torque ripple in induction drives (2015), low-switching-frequency MPCC for PMSMs, and comprehensive predictive strategies with sensorless options using reactive power control ([2018 thesis]). This review examines these foundational implementations—highlighting their merits, practical challenges in weighting factor tuning, computational demand, and system modeling limitations. By surveying empirical results and control methodologies, we seek to provide a cohesive understanding of early MPC applications in electric drives and inform future refinement and adoption.

II. LITERATURE REVIEW

Pre-2018 contributions include:

1. General MPC in Power Electronics (2014)

Vázquez et al. reviewed MPC applications in power converters and drives, highlighting its strengths in handling multivariable systems, constraints, and nonlinearities across induction machines and active front ends ResearchGate.

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2. FCS-MPC in Induction Machines (IET 2015)
Zhang et al. demonstrated predictive torque control in induction motor drives with reduced torque ripple, showcasing MPC's capability to enhance drive smoothness IET Research.

3. Model Predictive Torque Control (202) and Predictive Current Control
A 2018 doctoral thesis (pre-2018 work) evaluated flux weighting factor strategies, proposed reduced complexity predictive torque/current control with fewer voltage vectors, and implemented sensorless drive control through predictive modeling and observers ResearchGate.

4. Low-Switching-Frequency MPCC for PMSMs
Efforts to lower inverter switching frequency while retaining MPCC's dynamic performance were reported, showing MPC's flexibility in optimizing hardware wear and efficiency IET Digital Library.

5. Enumerative Nonlinear MPC for Linear Induction Motors (2012)
Thomas and Hansson proposed a predictive controller that significantly reduced switching frequency (~95%) in linear induction motor drives while maintaining tracking performance arXiv.

6. Continuous-Time MPC with Disturbance Decoupling (2017)
Errouissi applied CT-MPC to PMSM drives, combining Taylor-series-based predictive models with disturbance observers to decouple external disturbances for offset-free control IET Research.

Together, these works underscore MPC's early potential in drive control—delivering fast dynamics, constraint handling, and explicit control of inverter states—yet also point out areas such as computing load, model fidelity, and weighting complexity as critical issues.

III. RESEARCH METHODOLOGY

This review follows a structured methodology:

1. **Literature Identification**
○ Collected peer-reviewed sources up to 2017 featuring MPC implementations in electric drive systems—from journals and thesis repositories.
2. **Classification of MPC Types**
○ Categorized contributions into FCS-MPC, CT-MPC, predictive current control, model predictive torque control, and sensorless predictive strategies.
3. **Metric Compilation**
○ Extracted key performance indicators across studies, including torque ripple, switching frequency, dynamic response, and robustness to parameter variations.
4. **Comparative Analysis**
○ Evaluated each MPC form's advantages and practical limitations (e.g., computational burden, weighting factor tuning, model accuracy).
5. **Case Study Synthesis**
○ Used published experimental results, such as torque ripple reduction in IM drives or switching frequency reduction in MPCC, to illustrate outcome benchmarks.
6. **Insight Synthesis**
○ Derived unified observations on how MPC outperforms traditional control in constraint handling and multi-objective optimization, while spotlighting implementation obstacles.
7. **Future Guidance Formulation**
○ Emphasized future directions such as simplified weight tuning, explicit MPC, multi-phase extensions, and observer integration for reduced complexity and improved robustness.

This structured approach ensures comprehensive coverage and meaningful synthesis of MPC advancements in electric drives before 2018.

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VI. ADVANTAGES

- **Fast Dynamic Response and Ripple Reduction**: MPC directly optimizes torque/current control, significantly reducing torque ripple IET ResearcharXiv.
- **Constraint Handling**: Naturally incorporates inverter voltage/current limits and motor dynamics.
- **Multi-Objective Optimization**: Allows simultaneous control of torque, current, flux, and switching frequency ResearchGateIET Digital Library.
- **Sensorless and Disturbance Decoupling**: Extensions include sensorless control and CT-MPC with disturbance observers for robust performance ResearchGateIET Research.
- **Switching Frequency Reduction**: Techniques like MPCC reduce switching losses while maintaining performance IET Digital LibraryarXiv.

V. DISADVANTAGES

- **High Computational Cost**: Real-time optimization over prediction horizon places significant burden on hardware.
- **Weighting Factor Tuning Complexity**: Selecting appropriate cost function weights remains challenging ResearchGate.
- **Model Sensitivity**: MPC’s performance depends on accurate system modeling; parameter mismatches degrade control quality IET Research.
- **Implementation Complexity**: Observer-integrated or CT-MPC schemes increase design complexity and require precise calibration.
- **Limited Industry Adoption**: High computational and design overhead hinder widespread industrial use.

VI. RESULTS AND DISCUSSION

Comparative findings across implementations:

- **Induction Machine MPC** (IET 2015): Demonstrated notable reduction in torque ripple compared to traditional DTC and FOC IET Research.
- **Linear Induction Motor MPC** (2012): Achieved ~95% switching frequency reduction, significantly enhancing efficiency arXiv.
- **PM-SM Low-Switching MPCC**: Maintained dynamic performance while reducing switching losses IET Digital Library.
- **Predictive Control with Disturbance Observer**: CT-MPC achieved offset-free control amid mismatches and load disturbances IET Research.
- **Sensorless Induction and Multi-Phase Drives**: 2018 thesis showed reduced computational burden and effective multi-objective control with fewer voltage vectors ResearchGate.

These results affirm MPC’s advantages in nuanced drive control, though highlight the importance of reducing compute load and improving model robustness for broader applicability.

VII. CONCLUSION

Before 2018, MPC established itself as a versatile control strategy for electric drives—enabling optimized multi-variable control, reduced ripple, and constraint handling. Implementations across induction and PM motors showcased significant dynamic and efficiency gains. However, challenges such as computational load, weighting design, and model dependency limited industrial deployment. Addressing these drawbacks via simplified algorithms, explicit MPC, and model adaptation is essential for MPC to become a mainstream drive control solution.

VIII. FUTURE WORK

- **Explicit MPC**: Pre-compute control laws offline to reduce online computational demand.
- **Adaptive Weight Tuning and Learning**: Use auto-tuning or machine learning to dynamically adjust weights.
- **Model Order Reduction**: Develop efficient predictive models that balance accuracy and real-time feasibility.
- **Hardware Acceleration**: Leverage FPGAs or DSPs for real-time MPC implementation.

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- **Multi-Phase and Multi-Objective MPC**: Extend strategies to complex multi-phase drives and EV systems.
- **Integration with Observer Schemas**: Improve model robustness with adaptive disturbance observers.

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