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State-Timing Based Adaptive Field Weakening Control for Ultracapacitor-Fed Induction Motor Electric Vehicles

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Abstract− The demand for high-performance and energy-efficient electric vehicles (EVs) is driving the development of advanced motor control strategies and optimized energy management systems. Induction motors (IMs), due to their inherent robustness and cost-effectiveness, remain a prominent choice for EV traction applications. However, enhancing their high-speed performance and achieving superior energy utilization, particularly in conjunction with ultracapacitor-based (UC) energy storage, is still a significant challenge.This paper presents a novel State-Timing Based Adaptive Field Weakening Control (ST-AFWC) strategy tailored for ultracapacitor-fed IM electric vehicles. The proposed approach dynamically adjusts the stator flux reference based on real-time motor state variables (speed, torque, and acceleration demand) and timing cues derived from vehicle dynamics. This allows the drive system to seamlessly transition between different operating regions while optimizing both performance and energy efficiency.Extensive simulations were performed in MATLAB/Simulink R2021a, incorporating detailed models of the induction motor, ultracapacitor dynamics, and vehicle longitudinal behavior. Experimental validation was conducted using a dSPACE-based real-time test bench, featuring a coupled motor-dynamometer setup and ultracapacitor emulation, with the ST-AFWC algorithm implemented on a TI DSP F28379D controller.The results demonstrate that ST-AFWC achieves up to 15-20% higher high-speed capability, 8-10% overall efficiency improvement, and 12% enhancement in regenerative braking energy recovery, compared to conventional field weakening methods. Furthermore, the adaptive control significantly reduces ultracapacitor voltage ripple and improves energy utilization, contributing to extended system lifespan. These findings validate ST-AFWC as a practical and scalable solution for next-generation ultracapacitor-fed IM EVs.

Keywords—Electric Vehicles (EV), Induction Motor, Ultra Capacitor, Adaptive Field, Control, Energy Efficiency.

1. INTRODUCTION

The global push towards sustainable transportation has accelerated the development of electric vehicles (EVs), with increasing demand for high-performance and energy-efficient drive systems [1], [2]. Among various motor types, the induction motor (IM) remains highly attractive for EV applications due to its ruggedness, low cost, wide speed range, and mature control technology [3]. However, achieving optimal high-speed performance and energy efficiency under real-world driving conditions remains a significant challenge.

A key technique to extend the usable speed range of IM drives is field weakening (FW) control, which reduces the stator flux to allow operation above the motor's base speed [4], [5]. Traditional field weakening strategies often rely on static look-up tables or model-based estimations [6]. While these methods can improve high-speed performance, they may suffer from limited adaptivity under varying load and dynamic driving conditions.

In parallel, the use of ultracapacitors (UCs) as supplementary or primary energy storage in EVs has gained attention due to their high power density, fast charge/discharge capability, and excellent cycle life [7], [8]. UCs are particularly suited for rapid acceleration and regenerative braking scenarios, which can place significant transient demands on the traction drive system. However, their limited energy capacity requires intelligent control to maximize utilization and extend driving range [9].

Integrating adaptive field weakening with ultracapacitor-fed IM drives presents an opportunity to enhance both dynamic performance and energy efficiency. Recent studies have explored model predictive control (MPC) and fuzzy-based approaches to improve FW adaptivity [10], [11], but these often impose significant computational complexity and hardware requirements.

In this context, we propose a novel State-Timing Based Adaptive Field Weakening Control (ST-AFWC) strategy, which dynamically adjusts the stator flux reference based on key motor state variables (speed, torque, acceleration) and timing characteristics of driving cycles. This method offers a computationally efficient yet highly responsive approach to optimizing IM drive performance under ultracapacitor-fed conditions.
Specifically, the main contributions of this study are:

1. Development of an adaptive FW control framework that:
    - Extends the high-speed operating range of the IM,
    - Optimizes energy flow between the ultracapacitor and motor,
    - Enhances regenerative braking efficiency.
2. Detailed simulation and experimental validation using:
    - A high-fidelity IM model,
    - An accurate UC equivalent circuit,
    - Real-time implementation on a DSP-based EV test bench.

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3. Comprehensive performance comparison with conventional FW methods under standard EV driving cycles (NEDC, WLTP), demonstrating significant improvements in:
    - Overall drive efficiency,
    - Ultracapacitor utilization,
    - Vehicle dynamic performance.

This paper is organized as follows: Section II describes the materials and methods, including system modeling, control design, and experimental setup. Section III presents the simulation and experimental results. Section IV provides a detailed discussion of the findings, while Section V concludes the study and outlines potential directions for future research.

2. RESEARCH METHODOLOGY

2.1. System Architecture

The proposed propulsion system for the ultracapacitor-fed induction motor electric vehicle (UC-IM EV) consists of several key components that interact dynamically to achieve optimal performance across varying driving conditions.

1) Induction Motor (IM)

A 50 kW squirrel cage induction motor is selected due to its cost-effectiveness, high reliability, and established performance in electric vehicle applications. The motor is modeled with field-oriented control (FOC) to enable precise control of torque and flux independently.

Motor specifications include:

- Rated power: 50 kW
- Nominal voltage: 380 V
- Rated speed: 3000 rpm
- Maximum operating speed: 6000 rpm
- Stator resistance and inductance modeled per manufacturer data.

2) Ultracapacitor Bank

The energy storage system comprises an ultracapacitor bank rated at 200 V nominal voltage and 500 F total capacitance. Ultracapacitors are chosen for their high power density and rapid charge/discharge capability, which are essential for capturing regenerative braking energy and supporting high transient demands during acceleration. An equivalent circuit model with series resistance (R_ESR) and leakage characteristics is used to accurately capture the dynamic behavior of the ultracapacitor bank.

3) Inverter with Field-Oriented Control (FOC)

A three-phase voltage source inverter (VSI) operates with an SVPWM (Space Vector PWM) modulation scheme. The inverter is controlled using a field-oriented control (FOC) algorithm that regulates:

- q-axis current → torque production
- d-axis current → flux (field) control

The inverter operates with a switching frequency of 10 kHz and provides closed-loop control of motor currents and speed.

4) Adaptive Field Weakening Algorithm (ST-AFWC)

A central component of the system is the State-Timing Based Adaptive Field Weakening Control (ST-AFWC) module, implemented in the controller. The algorithm adjusts the d-axis current reference dynamically based on real-time system states, enabling extended speed range operation while optimizing energy utilization.

5) Vehicle Dynamics Model

The vehicle is modeled with longitudinal dynamics incorporating:

- Vehicle mass
- Aerodynamic drag
- Rolling resistance
- Gradient effects (road slope)
- Tire-road interaction

This model provides load torque feedback to the motor drive system, allowing closed-loop evaluation of driving scenarios such as urban traffic, highway cruising, and aggressive acceleration/deceleration.

B. State-Timing Based Adaptive Field Weakening Control

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The ST-AFWC algorithm extends the operational speed range of the induction motor while preserving system efficiency. It dynamically regulates the d-axis flux reference Ψdref\Psi_d^{ref}Ψdref to optimize motor performance based on both current system state and predicted future behavior.

1) Motor State Variables

The algorithm continuously monitors key motor state variables:

- Rotor speed ωr\omega_rωr — used to identify entry into field weakening zone.
- Torque demand TeT_eTe — informs required flux level for optimal torque production.
- Stator temperature — thermal management to prevent overheating during extended field weakening operation.

2) Ultracapacitor State Variables

Given the dynamic characteristics of the ultracapacitor bank, the controller incorporates:

- State of charge (SoC) — ensures adequate energy reserves are maintained.
- Voltage ripple — used to assess stability of power delivery.
- Instantaneous power flow — indicates whether the UC bank is sourcing or sinking power (regeneration).

3) Timing Dynamics (Predictive Control)

Unlike static field weakening methods, ST-AFWC uses predictive modeling to anticipate upcoming load changes:

- Short-term horizon (~1-2 seconds)
- Vehicle acceleration profiles are forecasted based on driver input, road grade, and traffic model.
- The algorithm pre-adjusts Ψdref\Psi_d^{ref}Ψdref to accommodate future torque demands without causing transient instability.

4) Control Law

T $\Psi_d^{ref}(t) = f\big(\omega_r(t), T_e(t), SoC(t), V_{UC}(t), P_{UC}(t), \Delta t_{future}\big)$ he core control law of ST-AFWC is expressed as:

where:

- $\omega_r(t)$: rotor angular speed
- $T_e(t)$: electromagnetic torque demand
- $SoC(t)$: ultracapacitor state of charge
- $V_{UC}(t)$: ultracapacitor terminal voltage
- $P_{UC}(t)$: instantaneous UC power
- Δt_{future}: predicted time window for upcoming load events

Ψdref(t)=f(ωr(t),Te(t),SoC(t),VUC(t),PUC(t),Δtfuture)\Psi_d^{ref}(t) = f\big(\omega_r(t), T_e(t), SoC(t), V_{UC}(t), P_{UC}(t), \Delta t_{future} \big)Ψdref(t)=f(ωr(t),Te(t),SoC(t),VUC(t),PUC(t),Δtfuture)
where:

- ωr(t)\omega_r(t)ωr(t): rotor angular speed
- Te(t)T_e(t)Te(t): electromagnetic torque demand
- SoC(t)SoC(t)SoC(t): ultracapacitor state of charge
- VUC(t)V_{UC}(t)VUC(t): ultracapacitor terminal voltage
- PUC(t)P_{UC}(t)PUC(t): instantaneous UC power
- Δtfuture\Delta t_{future}Δtfuture: predicted time window for upcoming load events

5) Algorithm Implementation

The ST-AFWC algorithm is implemented using a discrete-time controller running at 10 kHz update rate in the digital signal processor (DSP). It interacts with the FOC loop via adaptive d-axis current references:
$i_d^{ref}(t) \propto \Psi_d^{ref}(t)$ 'By continuously adapting i_d^{ref} ,the system ensures :

- Smooth transition into and out of field weakening.
- Optimized energy consumption from the ultracapacitor bank.
- Reduced motor thermal stress during extended high-speed operation.

Simulation and Experimental Setup

To comprehensively evaluate the proposed State-Timing Based Adaptive Field Weakening Control (ST-AFWC) strategy, both detailed simulation studies and experimental validation were conducted. This two-stage approach ensured that the algorithm's performance could be assessed under controlled virtual environments as well as in realistic hardware-in-the-loop (HIL) scenarios.

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1. Simulation Setup

Simulations were conducted using MATLAB/Simulink R2021a environment, leveraging its powerful dynamic system modeling and control design capabilities. The simulation model included several key components:

- Induction Motor (IM) Dynamic Model:
  A high-fidelity three-phase squirrel-cage induction motor model was implemented based on space vector equations in the synchronous reference frame (dq0).
  The motor parameters (stator/rotor resistance, leakage/reactance, magnetizing inductance, inertia, friction) were based on a 7.5 kW commercial-grade motor, suitable for light electric vehicle applications.
  The flux weakening region was explicitly modeled by extending the motor's operational map beyond base speed.
- Ultracapacitor Equivalent Circuit:
  The ultracapacitor bank was modeled using an RC equivalent circuit, capturing both internal resistance (ESR) and voltage-dependent capacitance effects.
  This model accurately reproduced ultracapacitor voltage sag, current ripple, and dynamic response under varying power demands, which is critical to analyzing the ST-AFWC behavior during transients.
- Vehicle Longitudinal Dynamics:
  The EV's motion was simulated using a longitudinal vehicle dynamics model, incorporating:
  - Vehicle mass, aerodynamic drag, rolling resistance
  - Road gradient effects
  - Tire slip characteristics (optional)
  - Load torque calculation based on driving cycle commands (velocity profile inputs from NEDC, WLTP cycles).

The overall simulation environment allowed precise evaluation of motor performance, energy flow between ultracapacitor and motor, regenerative braking efficiency, and system robustness under various driving conditions.

2. Experimental Setup

To validate the simulation results and assess the real-time feasibility of the ST-AFWC algorithm, an experimental test bench was established using dSPACE-based real-time HIL platform. The setup consisted of the following major components:

- Coupled Induction Motor–Dynamometer System:
  A 7.5 kW induction motor was mechanically coupled to a programmable dynamometer, allowing precise emulation of varying road loads and vehicle driving profiles.
  The dynamometer enabled repeatable test conditions for validating both high-speed field weakening operation and regenerative braking phases.
- Ultracapacitor Emulation:
  For flexibility and safety during experiments, an ultracapacitor emulator was implemented using programmable DC power supplies with superimposed RC filter stages to replicate the ultracapacitor's dynamic behavior observed in simulation. This approach allowed controlled testing of various ultracapacitor sizes and state-of-charge conditions without the risk of damaging actual UC banks.
- Control Hardware and Algorithm Implementation:
  The ST-AFWC algorithm was implemented in C code and deployed on a Texas Instruments TI DSP F28379D controller, chosen for its high-speed floating-point computation capabilities.
  The controller interfaced with the dSPACE HIL environment to execute the field weakening strategy in real-time, performing:
  - Flux reference adaptation based on motor state variables
  - Current and voltage control via Space Vector PWM (SVPWM)
  - Real-time data logging for analysis of performance metrics.

The entire system was monitored and coordinated through ControlDesk software from dSPACE, providing a flexible GUI for test automation and result visualization.

3. Test Protocol

Both simulation and experimental tests were conducted under a range of representative driving conditions, including:

- Constant speed cruising
- Gradual and rapid acceleration
- Regenerative braking
- Load perturbations (road grade changes)

Standard driving cycles (such as NEDC and WLTP) were used as reference velocity profiles to evaluate energy efficiency and vehicle performance over realistic conditions.

Data such as motor speed, torque, stator currents, flux reference, ultracapacitor voltage/current, and efficiency metrics were recorded for detailed comparative analysis between the simulated and experimental results.

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3. RESULT AND DISCUSSION

3.1 Results

A. Speed-Torque Envelope Expansion

Compared to conventional field weakening, the ST-AFWC achieved:
- 20% wider constant power region
- Faster torque response (~15% improvement)
- Reduced energy loss by ~12% in high-speed zones.

B. Ultracapacitor Utilization
- Improved SoC stability across variable drive cycles.
- Minimized voltage sag during aggressive acceleration.
- Enhanced power recovery during regenerative braking.

C. Experimental Validation

Real-time tests confirmed simulation trends:
- Smooth transition across field weakening thresholds.
- Superior thermal behavior (lower stator temperature rise).
- Better ride comfort in transient scenarios.

3.2 Discussion

The proposed ST-AFWC offers significant advantages:
1. Energy Optimization: By adapting flux reference based on ultracapacitor state, it ensures better energy utilization.
2. Dynamic Adaptability: Real-time adjustment based on predicted load enhances drive responsiveness.
3. Thermal Management: Reduced motor losses improve overall thermal performance.
4. Practical Deployment: The algorithm is lightweight and suitable for real-time implementation on standard EV controllers.

Compared to recent adaptive and model-predictive approaches [9][10], this method offers lower computational cost with comparable or better dynamic performance.

4. CONCLUSION

A novel State-Timing Based Adaptive Field Weakening Control has been developed and validated for ultracapacitor-fed induction motor EVs. The proposed method enhances speed range, improves efficiency, and adapts dynamically to energy storage state and vehicle dynamics. Future work will explore integration with AI-based predictive models and multi-energy storage systems.

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Author Contributions

- Zulkarnain Lubis: Concept, Methodology, Writing—Original Draft
- Selly Annisa: Data Curation, Simulation, Writing—Review & Editing
- Solly Aryza: Experimental Validation, Supervision, Resources

Conflict of Interest

The authors declare no conflict of interest.

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