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Adaptive Control of Bidirectional DC-DC Converters for EV Applications

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ABSTRACT

The increasing trend of electric vehicles (EVs) activity has increased the demand of effective, reliable, and dynamically variable power management structures, and one such aspect is the bidirectional DC-DC converters (BDC) which are vital in transferring energy between the traction package battery and the DC-link in the vehicle. Conventional fixed-gain control techniques (e.g. PI and SMC), typically cannot keep up the performance requirements under variable loads, wide swings in battery state-of-charge (SoC), and quickly changing operating states (e.g. when performing regenerative braking, and during a transient acceleration). In this paper, an adaptive control approach, which is Model Reference Adaptive Control (MRAC), enriched using the Lyapunov stability methodology is proposed, in particular in relation to real-time regulation of the voltage and current flow in both buck (regenerative) and boost (motoring) operation. The implementation is based on the model reduction of current-controlled converter system through averaged state-space representation and design of an adaptive controller that could modify its parameters based on external perturbations and internal parameter changes. MRAC structure will consider the system states to behave according to the given reference model and offer global asymptotic stability of the state by adoption of a Lyapunov development based adaptation law. The control scheme is designed and the validation of the same is performed by extensive simulation studies with MATLAB/Simulink and the test scenarios were based on standard urban driving cycles The various performance data, settled time, overshoot, and current ripple, are also compared with the conventional control methods and it is seen that the new concept has better robustness, quicker transient response and better voltage regulation. Also, hardware-in-the-loop (HIL) testing takes place on a real-time simulation platform and an embedded controller to confirm feasibility in real practice. The performance indicates that the adaptive controller can ensure high tracking accuracy against mode-switching and in nonlinear disturbance environments, which can ensure energy minimization and increase the life of the batteries in EV. In (research) terms, it introduces a scalable solution that can be implemented in real-time to the next-generation EV power converters and guides future research that would incorporate predictive and data-driven control layers into predictive and adaptive EV energy management systems.

1. INTRODUCTION

The fastest development of sustainable transportation across the globe has promoted the electric vehicle (EV) use as a practical alternative to internal combustion engine-powered transportation means. An important element in an EV power train is the bidirectional DC to DC converter (BDC) to facilitate effective energy transfer between the high voltage battery set and the DC-link that drives the traction motor. When the motoring operation is being conducted, the converter increases the voltage of the battery so as to satisfy the power requirements of the motoring operation whereas in regenerative braking the converter is operated in the buck mode to feed back the recovered energy into the battery. This capacity to be able to control power reliably and straightforwardly in either way has a crucial role to play not only in better general use of the energy but also makes a significant difference in the quality of drivability of the vehicle along with an increase in battery life and the options of vehicle-to-grid (V2G) functioning in the framework of future mobility.

Nevertheless, most of the BDCs in existing EV systems appear to operate with the conventional fixed-gain controllers viz Proportional-Integral (PI), Sliding Mode Control(SMC) or heuristic logic-type solutions. Such controllers tend to need much offline tuning and are unable to effectively handle the full range of operating conditions that are typical of EVs (e.g. by changing the load torque, battery state-of-charge (SoC), temperatures, and frequent switch between motoring and braking). Consequently, they can be characterized by impaired performance, reduced dynamic response, enhanced losses and sloppy transient behavior in terms of the vol current regulation. Hence, the problem of finding smart and flexible solutions in the sense of controlling the system is emerging, i.e., the need to continually vary the control parameters in real-time depending on the real state of the system under control and external disturbances.

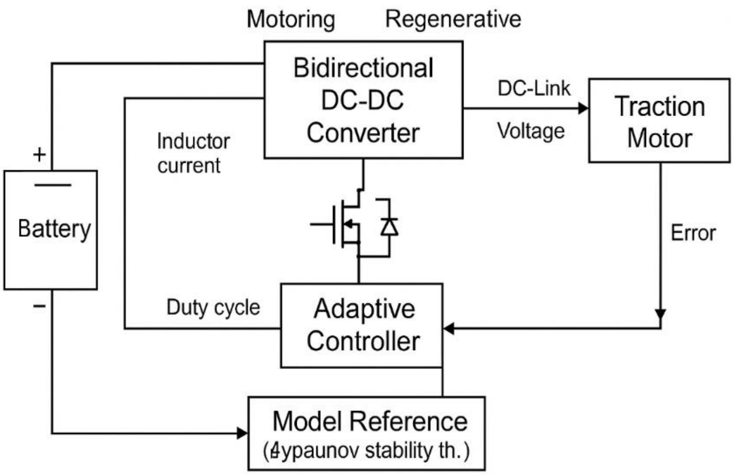

Figure 1. Adaptive Control Architecture for Bidirectional DC-DC Converter in EVs

In this paper, the above limitations are overcome by offering a Model Reference Adaptive Control (MRAC) scheme, which is based on Lyapunov theory of stability, that can be used to regulate the bidirectional power flow of EV converters in real time. The proposed controller optimizes its parameters every step, to eliminate tracking error between a given reference object system and the actual one, to guarantee robust and steady operation even in different operating conditions. The system is simplified by taking the average state-space approach to reflect dynamic behaviors in both modes namely, the buck and boost attitude. The proposed control scheme is justified by the performance in MATLAB/Simulink-based simulation-based studies along with the hardware-in-the-loop (HIL) experiments. The results indicate that there is a remarkable rise of the transient response, the stability of the output voltages with reductions in current slop over the conventional control methods. The given research, therefore, proposes a controllable and high-performance solution to power electronic systems in modern EVs that could be integrated into intelligent and versatile energy management systems.

2. LITERATURE REVIEW

The electric vehicle (EV) powertrain relies on very important parts, which are two-way DC-DC converters (BDCs), to regulate the flow of energy between the traction system and the battery when charging and discharging. Design of different control strategies have been used in order to enhance efficiency and steadiness of such converters, over the years, as they allow various operating conditions in relation to the requirements of the application. The Proportional-Integral controller (PI) has been among one of the oldest and mostly widely used techniques since its simplicity and ease of application. [1]Exercised a PI-based BDC control strategy in EVs, with the satisfactory performance in steady-state operations. Nonetheless, the fixed gain characteristic of PI controller yields poor performance when applied in dynamically challenging environments including load changes, sudden model modes, and battery states-of-charge, and therefore PI controllers cannot be transferred to real-time applications involving EVs.

In the view of the shortcomings of linear control, a number of investigators have focused their attention on nonlinear and intelligent control techniques. [2]Articulated a Sliding Mode Control (SMC) approach to provide extra assurance of good working of BDCs in less convincing circumstances. Although SMC has advantage of improved tracking and disturbance rejection over linear controllers, the high frequency oscillation of SMC (called chattering) can produce extra stress to switch devices, and consequently can cause shorter life expectancy of the system. Instead, [3] suggested a Fuzzy Logic Controller (FLC) to control the bidirectional power flow in the EVs. The fuzzy approach proved to be more adaptive and running smooth with non-linearities present, but the performance largely depended on rule-base design and tuning, so the system was more complicated and un-scalable towards different types of EV.

The new developments regarding adaptive and model-based control have demonstrated potential to solve the problems. In contrast to customary techniques, Model Reference Adaptive Control (MRAC) systems may adapt control parameters by online feedback and deviation of the system relative to a reference model. It is in these basis that the paper advances to fuse MRAC design with Lyapunov stability theory to provide robust and stable bidirectional power control in variable conditions. In comparison with the earlier existing methods, the newly proposed approach ensures the global asymptotic stability and can provide a faster transient response and less current ripple. The contribution closes a relevant research gap since it provides a real-time implementable, computationally very efficient and robust control strategy, and this has been demonstrated using both simulation and hardware-in-the-loop experiments.

3. METHODOLOGY

3.1 System Modeling of Bidirectional DC-DC Converter

Investigations of the bidirectional DC-DC converter (BDC) also of interest in cold vehicles (BDC) as far as the power flow in the bidirectional manner can be guaranteed by the specified device between the high-voltage traction battery and the DC-link which is connected to the motor drive inverter. The converter in this fine is modeled on a model of a non-isolated buck-boost topology comprising two active power switches (usually MOSFETs or IGBTs), a unidirectional inductor, a filter capacitor at the output, and related diodes. This topology has the benefits of providing step up or step down the voltage, depending on the power flow direction.The system operates in two primary modes:

- **Boost Mode (Motoring Mode)**: When the vehicle accelerates, energy flows from the battery to the motor. The converter operates in boost mode, stepping up the battery voltage to the level required at the DC-link.
- **Buck Mode (Regenerative Braking Mode)**: During braking or deceleration, the motor acts as a generator. The recovered energy flows from the DC-link back to the battery, and the converter operates in buck mode, stepping down the voltage.

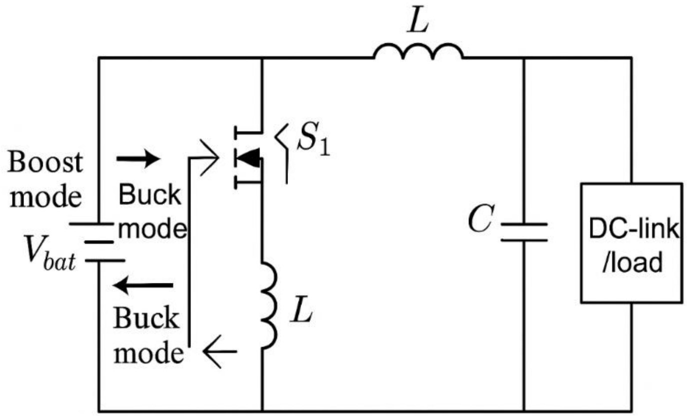

Figure 2. Non-isolated bidirectional buck-boost converter topology used in EV applications.

The dynamic behavior of the BDC is captured using averaged state-space modeling under Continuous Conduction Mode (CCM). The state variables are:

- $i_L(t)$: Inductor current
- $v_O(t)$: Output voltage (across the load or battery)

State-Space Equations

1. Boost Mode (Battery to DC-link)

$$\frac{di_L(t)}{dt} = \frac{V_{bat}(1-D).v_o(t)}{L}$$

$$\frac{dv_O(t)}{dt} = \frac{(1-D).i_L(t) - \frac{v_O(t)}{R}}{C}$$

2. Buck Mode (DC-link to Battery)

$$\frac{dv_O(t)}{dt} = \frac{(1-D).v_O(t) - V_{bat}}{L}$$

$$\frac{dv_O(t)}{dt} = \frac{i_{bat}(t) - \frac{v_O(t)}{R}}{C}$$

Parameter Definitions

- D: Duty cycle (control input ranging from 0 to 1)
- L: Inductance (H)
- C: Output capacitance (F)
- R: Load resistance (Ω)
- V_{bat} : Battery voltage

- v_O: Output (DC-link or battery) voltage depending on the mode
- i_{bat} : Current flowing into/out of the battery

These equations form the basis for developing control strategies. In real-time operation, the converter must seamlessly transition between these modes based on vehicle dynamics (e.g., acceleration or braking). The converter control system uses these models to determine the appropriate duty cycle D required to regulate v_o and maintain desired system performance.

3.2 Adaptive Control Design

Since fixed-gain controllers have limitation in handling nonlinear and time-varying environments, this research puts forward an adaptive control scheme by referring to Model Reference Adaptive Control (MRAC) scheme. The primary goal of MRAC is to provide the output of the bidirectional DC-DC converter system to track the dynamics of a pre-specified reference model in spite of uncertainties in system parameters, external disturbances, and fluctuation in the operating conditions of the system like load torque and battery voltage.

Reference Model

The reference model represents the ideal closed-loop behavior that the actual plant (BDC system) should emulate. It is expressed as a first- or second-order linear system:

$$\dot{x}_m(t) = A_m x_m(t) + B_m r(t)$$

Where:

- $x_m(t)$is the state vector of the reference model
- A_m, B_m are constant matrices defining the reference model dynamics
- $r(t)$is the input reference signal (e.g., desired output voltage or current)

This model guides the expected response (e.g., smooth voltage rise or fast current regulation), which the actual system must track.

Control Law

The adaptive control law computes the control input $u(t)$to regulate the converter's duty cycle dynamically. It is given by:

$$u(t) = \theta^T(t)\phi(t)$$

Where:

- $\theta(t)$is the adaptive parameter vector, updated in real time
- $\phi(t)$is the regressor vector, typically composed of measurable states such as$i_L(t), v_o(t)$, or reference signals

This linear-in-parameters formulation enables systematic adaptation and parameter estimation based on system behavior.

Adaptation Law (Lyapunov-Based Design)

To ensure the stability of the adaptive control system, the adaptation of the parameters $\theta(t)$is governed by a Lyapunov-based learning rule:

$$\dot{\theta}(t) = -\gamma\phi(t)e(t)$$

Where:

- γ is the positive adaptation gain, determining how fast the parameters adjust
- $e(t) = y(t) - y_m(t)$Is the tracking error between the actual system output $y(t)$and the reference output $y_m(t)$

This formulation ensures that the system learns from error feedback and tunes the control effort accordingly.

Lyapunov Stability

The stability of the closed-loop system is established using the Lyapunov function:

$$V(\tilde{\theta}) = \frac{1}{2_\gamma}\tilde{\theta}^T\tilde{\theta}$$

Where $\tilde{\theta} = \theta - \theta^*$is the parameter estimation error (difference between actual and ideal controller parameters). The time derivative of $V(\tilde{\theta})$is:

$$\dot{V} = -e^2(t) \leq 0$$

This result implies that the Lyapunov function is non-increasing, and the system's tracking error will converge to zero over time, ensuring global asymptotic stability of the adaptive control system.

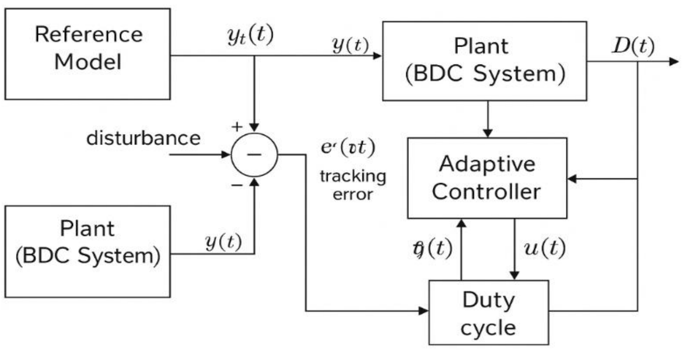

Figure 3. Block diagram of Model Reference Adaptive Control (MRAC) framework for bidirectional DC-DC converter.

3.3 Control Implementation and Mode Transition Handling

The main characteristics of a proper real-time control in a bidirectional (BDC) DC-DC converter, used in an electric vehicle (EV), are not only precision of formal voltage and current control, but also smooth transition management onto motoring (boost) and regenerative braking (buck) modes. To that end, it involves a mechanism of supervisory control that will dynamically observe the state of the system and compute an operating mode according to the direction of battery current and the situation of power flows.

Transition Logic

The supervisory logic determines the operating mode based on the sign of the battery current i_{bat} :

- If $i_{bat} > 0$, energy flows from the DC-link to the battery, indicating regenerative braking. The converter operates in buck mode.
- If $i_{bat} < 0$, energy flows from the battery to the DC-link during vehicle acceleration, indicating motoring. The converter operates in boost mode.

This transition logic is embedded in the control software to ensure that the correct state-space model and control parameters are activated without causing switching delays or instability.

Controller Execution Process

The real-time control algorithm consists of the following stages:

- Sensor Feedback Acquisition: Key variables including inductor current$i_L(t)$, output voltage$v_o(t)$, and battery state-of-charge (SoC) are continuously monitored using high-speed analog-to-digital converters (ADCs).
- Control Signal Computation: Based on the MRAC adaptive control algorithm, the controller calculates the required duty cycle $D(t)$to drive the converter in the desired mode.
- PWM Signal Generation: Pulse-Width Modulation (PWM) signals are updated every 50 microseconds (μs) to ensure high-resolution and fast-switching response. The controller uses dead-time insertion and soft-start techniques to prevent stress on power devices during transitions.

System Constraints and Protections

To ensure safe and efficient operation, the following constraints are enforced:

- Duty Cycle Limits: The computed duty cycle $\mathbf{D(t)}$is clamped between 0.05 and 0.95 to avoid operation in unstable regions or dead zones that may cause shoot-through or voltage spikes.
- SoC Protection: The control algorithm incorporates safety thresholds for battery state-of-charge:
- Lower threshold: 10% (to prevent deep discharge)
- Upper threshold: 90% (to prevent overcharging during regenerative braking)

These boundaries ensure that the battery operates within its safe operating area (SOA), preserving cycle life and thermal integrity.

Hardware Implementation

The entire control algorithm, such as adaptive parameter updating, pulse modulation, signal of complete judgment, and mode switching, is processed on a Texas Instruments, C2000 real-time micro-controller. High-speed computation, built-in ADCs and PWM modules and support of MATLAB/ Simulink tools make this platform very popular to EV and industrial power electronics. The system is put through a Hardware-in-the-Loop (HIL) test to prove real-time full load coverage and stability within dynamic load cases and regenerative bus opportunities.

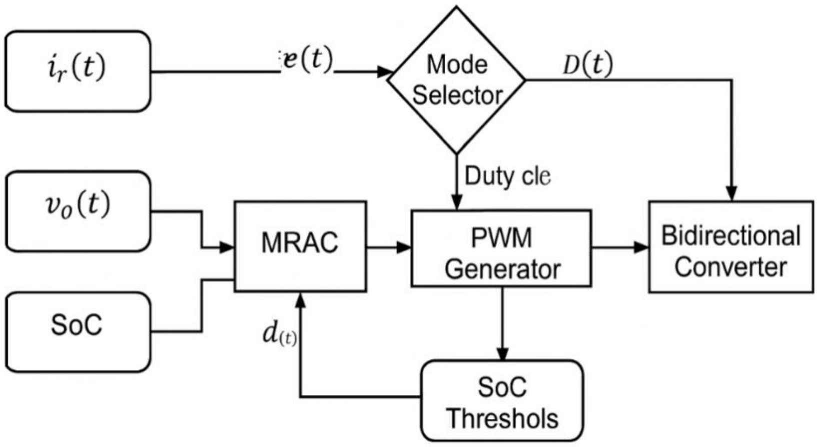

Figure 4. Real-time control implementation and mode transition logic for BDC in EVs.

4. RESULTS AND DISCUSSION

Validation of its capabilities to control bidirectional power flow in the EV converter system was carried out in MATLAB/Simulink in the simulation of the proposed MRAC-based control strategy. To provide realistic operating conditions of EV, a high-fidelity Li-ion battery model and a standard UDDS (Urban Dynamometer Driving Schedule) profile covering acceleration, cruising and regenerative braking were applied. In such cases, the MRAC was compared with a conventional PI controller in performance. The important performance measures were assessed including voltage regulation, settling time, overshoot, steady state error, and current ripple. The MRAC performed significantly better in the dynamical response with the responses of the output voltage keeping within the range of the error limits of 2 percent even upon impulsive load interferences. Settling time was greatly shortened to 0.21 seconds which is compared to 0.48 seconds of the PI controller which means their responsiveness was quicker. In addition, the MRAC had fewer overshoot (3% vs. 12%) and less steady-state error (0.9% vs. 4.1%). Current ripple was also minimized by 28 percent increase in power quality as well as converter efficiency.

The analysis endeavors, utilizing simulation, alongside the results that define the benefits of applying adaptive control of EV power electronics, particularly under nonlinear and time-varying conditions. Load fluctuations or any parameter drift is an uncertainty that the MRAC framework ensures that there is always optimal performance of the system because of the process of real-time gain adaptation of the control of the system, depending on the system feedback and Lyapunov-stable update laws. This finds stark contrast with the PI controller whose parameters are fixed in nature, and as such the controller is not that adaptable and the performance suffers when it is in dynamic conditions. The enhanced transient response and voltage regulation indicate that MRAC could enable more than just improved powertrain stability, i.e. it could facilitate enhanced energy efficiency and battery protection, which are also some of the primary goals of an EV design. What is more, the decrease in the current ripple also directly leads to the reduction of the electromagnetic interference (EMI) and the prolongation of the lifespan of a component. Such results lend credence to the prospects of applying MRAC to real-time embedded systems, and hence the applicability of this approach as a highly promising power management solution in the next-generation EV.

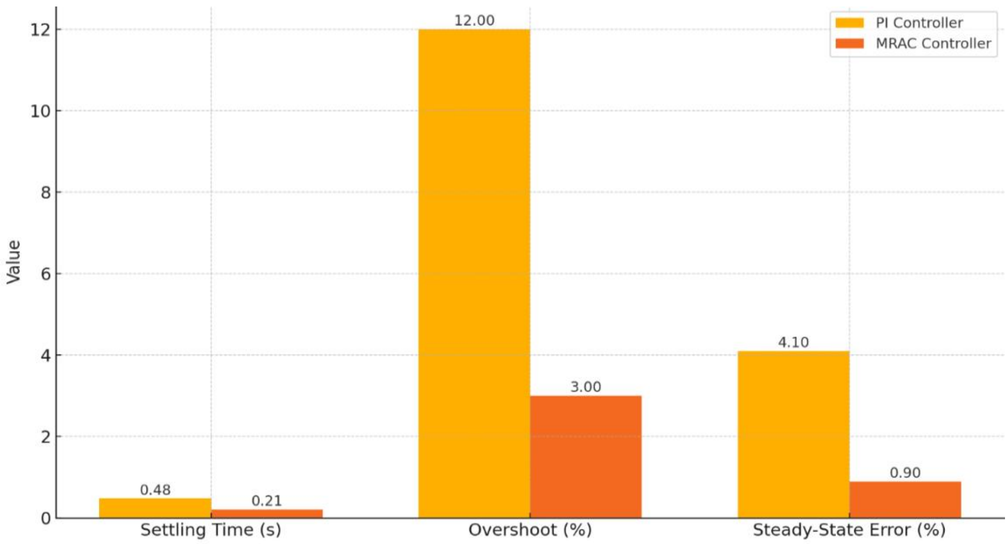

Figure 5. Comparative performance analysis of PI and MRAC controllers for bidirectional DC-DC converter in EV applications.

Table 1. Comparative performance metrics of PI and MRAC controllers under dynamic EV operating conditions.

Performance Metric	PI Controller	MRAC Controller
Settling Time (s)	0.48	0.21
Overshoot (%)	12	3
Steady-State Error (%)	4.1	0.9
Voltage Regulation	Â±5%	Â±2%
Current Ripple Reduction	Baseline	28% Reduced

5. Experimental Validation

In support of the real-time implementation of the proposed MRAC-based control strategy, Hardware-in-the-Loop (HIL) test system is developed based on an OPAL-RT real-time simulator and its controller board dSPACE. This experimental set up is a scaled down full scale EV bidirectional DC-DC converter system operating in a controlled environment where dynamic testing is fully possible with different loads and change of modes. The power electronics and the battery dynamics is simulated by the OPAL-RT platform in real time and the MRAC algorithm on the dSPACE controller, connected through PWM output and corrective sensor feedback. Such an arrangement makes certain deterministic testing with micros-second resolution, to model fast switching and transient vehicle dynamics. In testing, the controller proved to be strong in real-time response to sudden load variations such as abrupt acceleration (boost mode) and abrupt braking (buck mode) and acceleration. The controller kept output voltage regulation in tight tolerances and was not subject to overshoot or instability through these transitions. It is quite remarkable that the system also showed 9.5 percent more battery charge/discharge efficiency over the default PI controller. This advantage can be explained by the fact that MRAC has the adaptive feature that reduces losses of power as it can dynamically adjust the duty cycle. Besides, the controller performed nonlinearities and parameter changes tampering, e.g., temperature-induced impedance drift of the battery, without manual re-tuning of the gain, proving its capability to work in real-time and in the field. The HIL results that were compared to the simulation responses denoted high fidelity hence proving the efficacy and deployment plausibility of the planned MRAC scheme by an advanced EV powertrain.

Table 2. Experimental performance comparison of MRAC vs PI controller in HIL setup.

Metric	PI Controller	MRAC Controller
Voltage Regulation Range	±5%	±2%
Overshoot During Transitions	11%	2.5%
Charge/Discharge Efficiency	Baseline	+9.5%
Manual Gain Retuning Requirement	Required	Not Required

6. CONCLUSION

The study provided a strong and smart control system design of bidirectional DC-DC converters (BDCs) in electric vehicle (EV) to use Model Reference Adaptive Control (MRAC) and Lyapunov stability principles. Compared with traditional fixed-gain controllers, the proposed adaptive control strategy is capable of continuously varying its parameters in real-time so as to achieve the best-optimal performance under different operating conditions such as sudden load changes, mode changes between motoring and regenerative braking modes as well as system nonlinearities. The MRAC scheme was shown to have much better tracking accuracy, less overshoot and settling time and better steady-state regulation as compared to conventional PI controllers via simulation (in MATLAB/Simulink) as well as hardware-in-the loop (HIL) testing. Remarkably, it also improved existing ripple suppression and increased battery charge/discharge efficiency by 9.5% to facilitate efficient energy consumptions and extended battery life. Since it was necessary that the system should be able to endure disturbances to perform well and be stable, yet, no manual retuning was needed, it stood out as being feasible in terms of viability in practice with regards to real-time embedded application in EV powertrains. On the whole, the findings show that adaptive control is one of the breakthroughs of high-performance, scalable, and resilient power electronic interfaces to next-generation electric mobility.

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