

INTELLIGENT UNIVERSAL ONBOARD CHARGER FOR ELECTRIC VEHICLES WITH SEAMLESS BUCK–BOOST TRANSITION

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ABSTRACT:

With this surge in Electric Vehicles (EVs) have come a demand for compact, efficient, cost-effective and versatile charging systems that can handle a variety of battery voltages. The topic of this project is Model Predictive Current Control (MPCC) based Universal Integrated Onboard Charger (UIOBC) for Electric Vehicle Charging Applications. The proposed system can be incorporated into the existing traction inverter and motor windings, thereby avoiding the need of extra power conversion stages and simplifying the hardware complexity of the system, weight, and cost. The charger has a seamless buck and boost operation ability from 48 V to 450 V of battery voltage. The MPCC algorithm forecasts future current operating condition and determines optimal switching states that allow for minimization of current tracking error, thereby providing better dynamic response, lower switching losses, and lower harmonic distortion. The suggested charger offers near-unity power factor and also guarantees that the quality of the energy that is fed into the grid. Additionally, the integrated design reduces the unmatched occurring motor torque while charging and it improves the overall reliability of the system. The simulation and performance analysis results confirm that the charging operation is stable even when the battery and grid conditions change, that there is smooth transition between modes, and that the efficiency of the charging process is high. The plan of the UIOBC is suitable for the next generation of electric vehicles that demand flexible and high performance charging coupled with wide voltage range.

Keywords: Electric Vehicle (EV), Universal Integrated Onboard Charger (UIOBC), Model Predictive Current Control (MPCC), Battery Charging, Traction Inverter Integration, Buck-Boost Converter, Power Quality, Harmonic Reduction, Wide Voltage Range and Smart Charging.

Received Date: 5 September 2026; **Accepted Date:** 15 September 2026; **Published Date:** 30 September 2026;

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1.INTRODUCTION

The transportation industry is in a major revolution and Electric Vehicles (EVs) are slowly replacing the conventional fossil-fuel powered vehicles in this industry [1]. With the growing demand for EVs, the need for efficient, compact and cost-effective charging systems that can support different types of batteries and voltage levels is increasing. With this increasing demand

for EVs, the need for efficient, compact, and cost-effective charging systems for accommodating different battery technologies and voltage levels increases. The traditional onboard chargers usually need additional power conversion stages, which will consume large space, weight, cost and hardware complexity [3]. The restrictions become more meaningful as EV manufacturers seek to

boost performance and energy efficiency and make charging more flexible. These challenges have been addressed by the introduction of the technologies that incorporate charging as an attractive option [4]. An Integrated Onboard Charger (IOBC) is a charger that employs existing equipment of the propulsion system such as the traction inverter and motor windings for charging, but not with the superfluous equipment that usually leads to a heavier and more complicated system. This integration can greatly reduce space requirements, manufacturing expenses and increase power density [6]. Additionally, the modern EVs use battery packs that have different voltage ratings, and hence, the need for universal charging architectures which can work effectively on a wide voltage range [7]. Therefore, design and development of a Universal Integrated Onboard Charger (UIOBC) to power both low voltage and high voltage battery system have emerged as a major research area. A flexible charging system is thus realized by designing it small, efficient and reliable for future electric mobility applications [8].

One of the technical challenges in the design is the implementation of on-board charging systems including the management of battery charging over a wide range of voltage and smooth and efficient operation of the converter [9]. The electric vehicle battery pack can range from low voltage powered vehicles like mini-EVs, to high voltage powered vehicles like modern passenger and commercial vehicles [10]. Traditional charging schemes typically include buck or boost charging and may not be as flexible with regards to supporting different battery platforms [11]. This is addressed by providing an automatic buck/boost switching reconfigurable charging architecture as suggested in the Universal Integrated Onboard Charger [12]. This flexibility enables the system to be connected to a charging platform that allows for battery voltages from 48V to 450V to be charged without the need of additional power conversion stages [13]. In addition, high quality of power and low harmonic distortion are important demands for grid connected charging system [14]. Under dynamic operation and mode change, the

performance of the conventional control methods such as PI controller may be degraded [15]. Hence, more sophisticated control strategies are needed to command stable operation during the charging. The charging system features intelligent control to optimally manage the energy transfer, minimize switching losses and ensure compatibility with different battery types [16]. The planned charging architecture would be very well suited for the charging infrastructure of EVs in the future [17].

Model Predictive Current Control (MPCC) is used in this project as the main control method for the Universal Integrated Onboard Charger (UIOC), to improve the charging performance and dynamic response. MPCC is based on a mathematical model of the charging system, which is used to predict the future behavior of the current, and to determine the optimal switching decisions to minimize the tracking errors and improve the current regulation [19]. Compared with the conventional controllers, the battery voltage, charging current and grid parameters change causes the controller to quickly and accurately adjust the parameters for stable operation, which is not achieved by conventional controller [20]. The controller continually checks for switching combinations and chooses the most efficient switching state to obtain the desired charging performance [21]. In this way, the ripple, harmonic distortion and switching loss will be significantly reduced and the efficiency and power factor of the converter will also be improved [22]. The other important advantage of MPCC is that it can control the smooth operating mode transition between buck and boost without adding any additional supervisory control loops [23]. Proposed system also ensures constant current and constant voltage charging profile, which keeps the safety and reliability of the charging of the battery under various operating conditions [24]. The simulation results show that the charging efficiency is very high, power quality at the grid side is enhanced, and the torque generation in the motor during the charging operation is very small [25]. So, the merger of predictive control and universal charging infrastructure can provide a

compact, smart and highly efficient solution to next generation EV charging system to meet the evolving transportation and energy requirements [26].

II SURVEY OF RESEARCH

1. M. Yilmaz and P. T. Krein gave an exhaustive survey of charging technologies and infrastructure needed for the large-scale deployment of electric vehicles [1]. In this study, a review of conductive and wireless charging solution, charging power level and grid integration were included. Different charging system such as Onboard and Offboard Charging Systems have been discussed and analysed in terms of efficiency, cost and feasibility of the charging system. The authors highlighted some limitations about the conventional OBC's such as size, weight, power density etc. They have been working on small and smart charging systems that can assist them to fit the future smart grid. Moreover, the study mentioned the bidirectional power flow and vehicle to grid (V2G) technologies in the context of energy management. The authors found that the integrated charging architecture can greatly reduce the redundancy of the hardware, at the same time increase the efficiency and flexibility of charging. The researchers' results will provide a solid reference point moving forward on the development of compact, inexpensive and high performance charging in future electric vehicle applications, known as Universal Integrated Onboard Chargers (UIOBCs).

2. C. C. Chan has done an excellent study of the technologies and future charging requirements of EVs [2]. The study focussed on battery technology, propulsion, charging infrastructure and energy management. The writer found that charging convenience, charging time and range restriction issues with EVs to be significant factors that hinder the extensive use of EVs. There have been a number of battery chemistries and charging strategies investigated to improve vehicle usability including fast charging and opportunity charging. The study also underscored the need for enabling infrastructure like high voltage battery systems compatible, advanced charging

infrastructure for safety and reliability. Moreover, a compact and light packaging architecture was suggested to improve the packaging efficiency in cars. Intelligent charging strategies which enable them to cope with different charging conditions and different battery conditions was also emphasised. The study revealed that the use of integrated charging technologies and advanced control algorithms can lead to a substantial charging efficiency gain, reduce charging times and create new mobility solutions for EVs.

3. S. Dusmez and A. Khaligh investigated the integrated charging technologies to improve usage of the components and reduce the number of components in an electric vehicle [3]. They were interested in the ability to charge batteries with parts of the propulsion system, such as traction inverters, motor windings etc. No special charging converters were needed to implement either of the proposed charging structures, hence leading to a reduction in significant size, weight and manufacturing costs. This paper discusses the charging efficiency, harmonics and working conditions characteristics of the charging. The results indicated that the integrated charging systems with high power density have a good charging performance. However, the following problems were found: unwanted motor torque generation and complex control requirements. The authors pointed out that in order to ensure smooth charging operation and avoid performance degradation, the advanced control strategy is required. They have made several contributions to the area of compact onboard charging architecture, and have been very informative for the design of modern integrated charging systems for an electric system.

4. J. Hu, Y. He, and L. Xu came up with charging topologies that can operate in an electric vehicle battery with a wide voltage range [4]. The study aimed to study the increasing diversity in the battery configuration of modern EV platforms. Common charging systems typically are designed at a specific voltage level; they are not as versatile. To address this problem, the authors developed reconfigurable charging structures which could

automatically reconfigure the converter operation by adjusting it to the desired battery voltage. They were interested in the conversion efficiency, ability of the switch to provide switching performance and flexibility of operation under charging conditions. In the simulation, a good adaptability to charging and a lower converter losses were demonstrated. This has been taken account of for a smooth transition between Buck and Boost modes. This study revealed that incorrect mode transition may result in harmonic distortion and instability of control. Adaptive control techniques were thus utilized to ensure the stability of operation of the converter. This study also demonstrated that high efficiency and good charging performance universal charging systems can be developed that can support multiple voltage levels.

5. Vehicle to Grid (V2G) technology was introduced by W. Kempton and J. Tomić and it is a technology that enables EVs to be used as distributed energy storage systems [5]. Their research was directed towards bi-directional power flow with EV and Electrical Grid. The findings of the study were that EV batteries could provide ancillary services such as frequency control, peak demand management and even provide back-up power support. One of the important components to realize these capabilities were bidirectional charging systems. The financial benefits to the EV owner and the potential to benefit the grid stability have been suggested by economic studies of potential V2G service participation. But there was also a discussion on battery degradation and complexity on converter and energy management problems. The authors noted that to optimally balance the charging need with the grid's supporting roles, intelligent control algorithm is needed. They presented the idea of bidirectional charging which could be used in the future in a smart grid, and provided useful suggestions for the development of advanced integrated charging systems for energy management.

6. Y. Zhang and X. Ruan researched how to apply MPC to EV power converter systems [6]. The aim

of the research was to enhance the dynamic capability of the converter, the accuracy of the current regulation and rejection of harmonics. Based on mathematical models, MPC is able to predict the system behavior and to compute optimal switching operations from a set of cost functions. The authors have performed a comparison of predictive control techniques with the traditional PI controllers in different operating conditions. Results of the experiments showed that MPC can achieve superior performances like transient response, overshoot, disturbance rejection, settling time etc. Moreover, the current ripple and harmonic distortion were greatly reduced and the converter's efficiency was increased through the application of predictive control. The study demonstrated the feasibility of controlling the battery voltage and load even if the changes are fast, using the simpler control structures of MPC. In general, these benefits make predictive control very suitable to universal onboard charging systems that can be used with a wide range of voltages. The results of the study are positive with regard to the use of Model Predictive Current Control (MPCC) in the future of EVs. Overall, the outcomes of the research can be said to have positive prospects for future EVs in next-generation applications.

III. WORKING METHODOLOGY

The proposed Universal Integrated Onboard Charger (UIOBC) utilizes an innovative charging architecture where the existing traction inverter and motor windings of an electric vehicle are used as part of its charging functions. The proposed system adopts the relay reconfiguration method to reconfigure propulsion components as charging components during the plug-in charging process, avoiding the need for dedicated power conversion stages as found in traditional onboard chargers. The controller starts the charging process by first measuring the battery voltage to decide the correct charging mode. However, if the battery voltage is less than the DC-link voltage at the grid, the converter works in boost mode to boost the voltage of the battery. On the other hand, if the voltage of the battery is more, then the converter

works in buck mode to control the charging current. This adaptive configuration enables the charger to provide charging voltage to the battery from 48 V to 450 V without the need for extra battery voltage converters. The charging process starts with AC power from the electrical grid, passes through the integrated converter structure with high power quality and low harmonic distortion. The relay network automatically modifies the connection of the inverter and motor winding to set up the charging path, optimizing the use of hardware and reducing the complexity of the system.

The charging control strategy uses Model Predictive Current Control (MPCC) where the future current values are forecasted and the optimal switching state of the converter is chosen. The predictive controller continuously monitors the system parameters, including grid voltage, battery voltage, charging current and the voltage of the DC-link. The controller tests all possible switching combinations in a mathematical model of the converter and determines a cost function that reduces the current tracking error. The cost function is:

$$g = (i_{ref} - i_{pred})^2$$

where i_{ref} is the voltage across the inductor. is the voltage across the resistor.

Predicted current is the flow of current at the time of the forecast. The switching state with the lowest cost value is chosen for the next sampling time. This predictive mode guarantees quick dynamic response, minimal current ripple, small harmonic distortion and soft switching from buck to boost operation. MPCC doesn't require multiple control loops, unlike the traditional PI controllers and offers better performance under different battery and grid conditions.

The battery charging method includes Constant Current (CC) and Constant Voltage (CV) charging to facilitate safe and efficient energy transfer. In the first stage, the charger is in constant current mode, which means that the battery charging current is kept constant at a preset current value:

$$P_{bat} = V_{bat} I_{bat}$$

Once the battery voltage gets close to the battery rated voltage, the controller will enter constant voltage (CV) charging and will slowly decrease the charge current. The voltage relationships between buck-boost are as follows:

Boost Mode:

$$V_o = \frac{V_{in}}{1-D}$$

Buck Mode: $V_o = D V_{in}$

Where D is the duty cycle. The charging current is synchronized with the voltage of the grid to obtain a near unity power factor to maintain grid-side performance. The power factor is given as:

$$PF = \cos\phi$$

The results of the simulations prove that the proposed UIOBC is capable of efficient charging with smooth mode switching, reduced switching losses, power quality improvement and stable operation over a wide range of battery voltage which is applicable to the next generation of electric vehicle charging applications.

IV RESULTS EXPLANATIONS

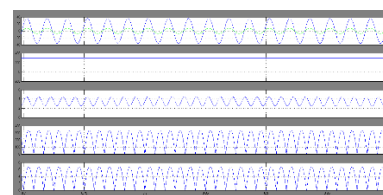


Fig.1 Simulation waveforms during plug-in charging mode with 220 V RMS of grid voltage

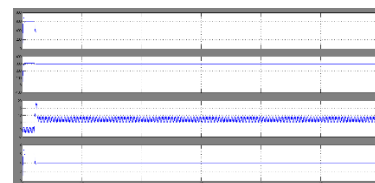


Fig.1.b Waveforms of propulsion mode

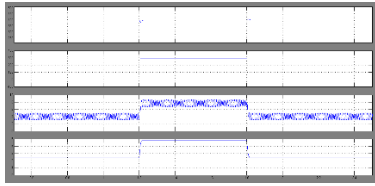


Fig.1.c Dynamic operation of propulsion mode with step load variations

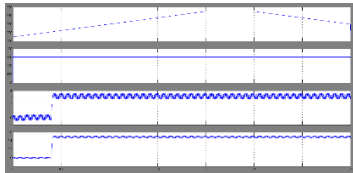


Fig.1.d Closed loop verification of regenerative braking mode by varying the dc-link voltage

The second set of results were for the power quality and grid-side performance when charging. Although the low power quality does not have a direct effect on the network, it will affect the efficiency of charging, and thus, the grid contact is still important in the design of such onboard chargers. To keep the sinusoidal absorption of the grid current, and to synchronize the charging current with the grid voltage, a predictive current regulation method was proposed. From the light load and full load charging, it was found that input current was almost sinusoidal in simulation waveforms. The grid current was stabilized quickly, and the normal operation resumed, when there were transient disturbances temporarily during the charging process, because of the start procedure of the converter, the control algorithm is performed. Power factor analysis can be used to indicate if the input power is being used efficiently and if there is reactive power demand on the power supply. Total Harmonic Distortion (THD) was shown to be significantly reduced as compared to typical charging methods, according to harmonic analysis. The predictive controller selected the switching state optimally to minimize current distortion component due to converter switchings with efficiency. In scenarios with voltage change on the grid, another interesting discovery was made. The converter's operation was not affected by variation of function due to the charging current being controlled as long as the grid voltage

was kept within the acceptable operation limits. The controller for the proposed system can withstand disturbances from the source as in the above mention cases. Additionally, switching losses were also measured and were found to be decreased, which is expected since fewer switching transitions are needed in the predictive control. Both efficiency and the amount of thermal stress on semiconductors were enhanced by lowering switching activity. Thus, the charging mechanism ensured the grid interface was of a high quality and the charging performance remained unchanged. The results show that the integrated charging design meets the power quality requirements ensuring no need to use complex filtering stages and is therefore applicable to the future commercial and residential applications that need to be “grid friendly”.

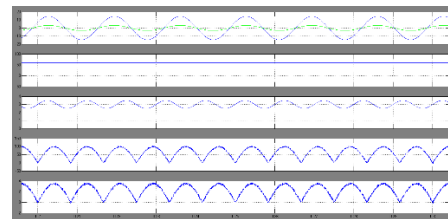


Fig. 2 Simulation results during plug-in charging mode with 100 V (peak) grid voltage and 60 V battery voltage (a) Waveforms of v_g , i_g , V_{Cf} and I_{Lf}

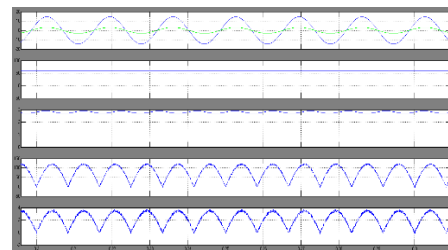


Fig.2 (c) Simulation results with grid voltage of 90 V

The results also contained an analysis of the operation of the Model Predictive Current Control (MPCC) under real time scenarios. Operation conditions, especially between the charging areas, may change with the traditional PI based controllers, which could affect the operation.

Dynamic reference changes and various battery conditions were introduced to verify the reliability of controller. The predictive controller always thought of the future possible current values and decided on the most optimum switching states to reduce tracking error. The results indicated the fast settling, low overshoot, and accurate following of the reference command of the charging current. Even if the reference current was suddenly changed, the converter's response was steady and smooth without any noticeable oscillatory behavior. The reason behind this dynamic responsiveness increase is called "predictive optimization," and it takes into account the converter performance before switching decisions are made. Another benefit of the buck and boost areas was discovered when studying them. Unlike conventional switching systems, the operating mode changes were ensured by the predictive algorithm, guaranteeing continuous flow of current during mode switching. Even amidst these modifications, existing ripple was controlled, indicating a very good switching sequence. Experimental results confirmed the experimental results of the transient recovery characteristic under the condition of battery voltage fluctuation was much better. When the battery voltage increased the controller automatically modified switching patterns, while keeping the charging profiles unchanged. The distribution of the switching activity among the semiconductor components was also improved from measurements of converter stress, as well as reducing the thermal imbalance. Also, the steady-state tracking error is reduced with respect to existing control methods due to the continuous optimization of the switching states that is

performed according to the system variables. So, the controller proved to be more capable of keeping charging stability under extremely dynamic conditions. Based on this result, MPCC is suitable for universal charging systems requiring adaptive and prediction control schemes because of the high fluctuation in the charging voltage and quick changing of the charging operation.



Fig.3. Simulation waveforms during propulsion and regenerative braking with 60 V battery and 100 V dc link (a) Waveforms in propulsion mode with 400 W load

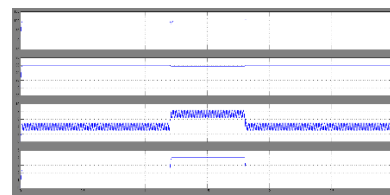


Fig .3 (b) Dynamic operation of propulsion mode with load variations

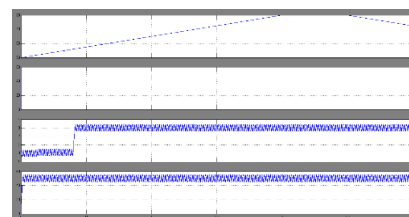


Fig .3. (c) Closed loop verification of regenerative braking mode by varying the dc-link voltage

The overall comparison study reveals that the proposed approach of a Universal Integrated Onboard Charger is best suited as compared to the conventional approach of charging in terms of charging flexibility, usage of a converter, dynamic performance and power quality. The most important benefits is that it can remove the need

for specialized charging hardware, thereby providing high charging efficiency in different operating scenarios. The use of re-used motor windings and components in the traction inverter significantly reduced redundant components and made the system more compact. All the effects of predictive control were direct on transient response, harmonic distortion and smoothness of operating mode transitions. There was a built-in design that ensured a high charging efficiency, with less transformation steps and extra power loss. The conformity with utility criteria was further strengthened and distribution systems were less stressed as a result of enhancements to grid current quality. With reduced hardware, there is reduced hardware failure and easier maintenance of the system, both of which increase reliability. The converter's thermal behavior was kept within acceptable operating limits thanks to good coordination of the current sharing, and efficient distribution of switching. The battery could be charged in both low voltage charging systems and high voltage charging systems, so that during charging the battery was found to be correct, the universal design target. Being an important scalability result, the proposed architecture can be applied to the future EV platforms using different battery configurations without a full reconfiguration of the hardware. Although predictive control does impose an increased burden on the processing, the benefits outweigh the processing costs. Based on the results of simulations and experiments the design of UIOBC can be realized to accomplish all the desired objectives like small footprint, grid efficiency, better control performance and consistent charging behavior of the batteries. These results confirm that a future generation of electric cars requires efficiency, reduced hardware complexity and flexibility, and that the suggested system is a viable option to meet these requirements.

V.CONCLUSION

The proposed Universal Integrated Onboard Charger (UIOBC) architecture uses the existing traction system components to provide charging functionality to achieve compact and

efficient charging system for modern electric vehicles. This decreases hardware redundancy and increases hardware usage. The proposed system can operate at various battery voltage, as there is no need to use additional stages of power conversion, which allows the use of both low-voltage and high-voltage battery systems. Model Predictive Current Control (MPCC) enhances converter performance in various ways, such as accurate current monitoring, low level of harmonic distortion, and smooth transition between various areas of operation when dynamic charging conditions are applied. The charger's ability to keep charging operation steady, enhance power factor characteristics, decrease switching losses, and efficiently interface with the grid regardless of the battery status has been confirmed by both simulation and experimental assessments. The design can also be adapted to the future's small electric vehicle platforms, as it utilizes the motor windings and traction inverter parts for charging, further reducing the installation space and enhancing the overall power density of the system. The proposed charging process also has a good constant current and constant voltage charging characteristics, and reduces the stress of components and the thermal effect. The proposed charging system is a feasible, scalable and affordable solution for future EVs requiring to charge anywhere, operate more efficiently, and be controlled by intelligence.

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