Multiple Harmonics Reduction Method for the Integrated On-board Battery Charging System of Hybrid Electric Vehicles

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This paper proposes a multiple harmonics reduction method for the integrated on-board battery charging system of hybrid electric vehicles (HEVs). The proposed system allows the starter generator and its drive inverter to operate as a battery charging system. The reconfiguration of the system results in the elimination of the conventional on-board charger (OBC), thereby reducing the system volume, weight, and manufacturing cost of HEVs. In addition to the control method of the battery charging system, a harmonics compensation method is presented to improve the performance of the charging system. Different harmonics can be expressed as a unity variable in the synchronous reference frame by utilizing the phase sequence of the harmonics. The unified variable reduces the harmonic controller and simplifies the gain value selection. Simulation and experimental results verify the effectiveness of the integrated on-board battery charging system and its control method.

Keywords: hybrid electric vehicles, integrated charging system, on-board charger, harmonic compensation method

1. Introduction

Recently, the social concerns about environmental pollution and exhaustion of fossil fuel are increasing continuously. Accordingly, the interest in electric vehicles (EVs) and hybrid EVs (HEVs) is increasing continuously due to the demands of the effective energy usage and decrease in contamination materials (11-15). The internal combustion engine (ICE) vehicles are also being continuously developed in terms of driving efficiency and emissions. However, it cannot be a fundamental solution against the fuel efficiency and emissions.

Compared to ICE vehicles, HEVs can be an effective alternative owing to their use of dual traction power, i.e., electrical and mechanical power (16-19). In addition, the frequent idling of vehicles in downtown causes increase in the pollutant emissions, whereas HEVs prevent it by utilizing the starter generator (SG) system. While the deceleration of an HEV, the regenerative braking mode improves the driving efficiency by converting kinetic energy into electrical energy. These advantages, however, result in a greater number of system components and complicated circuit configuration compared to ICE vehicles (9-12).

In this paper, the integrated on-board battery charging system is proposed to overcome these limitations of HEVs. In the conventional HEVs, the starter generator system and on-board charger (OBC) are separately constituted. These power converters operate as only their role, thereby inevitably increasing the system volume, weight, and manufacturing cost. However, the proposed system that consists of conventional starter generator system and additional power relays can be operated as both starter generator system mode and battery charging system mode. In other words, when the integrated on-board battery charging system is applied to HEVs, not only the number of power converters can be reduced due to the removal of the conventional OBC, but also the power density of the system can be increased.

The power quality is a crucial evaluation index of power converters including the chargers for HEVs. The harmonics produced by using non-linear loads degrades the power quality of the output currents and generates the additional power losses and premature ageing in electrical equipment (13-14). A variety of studies were conducted in the past to compensate for these unintended components (17-22). The attenuation method involving the use of hardware components, such as active or passive filter, can be a solution for the distributed generation system. However, this compensation method causes an increase in the total system components; thus, it cannot be an optimal solution for an OBC. A multiple harmonic reduction method is proposed using the software techniques and switching operation of power converter to fulfill the grid regulation concerning the harmonic containment. The proposed compensation method specifically focuses on the reduction of the low order harmonics such as 3rd, 5th, and 7th that have a dominant influence on the system efficiency and power quality of a single-phase system. The effectiveness of the proposed circuit configuration and its control method including the harmonic compensation method are verified using both simulation and experimental results.
2. Integrated On-board Battery Charging System

As shown in Fig. 1, the circuit for the integrated on-board battery charging system consists of a starter generator system and seven power relays. Depending on the states of power relays, the proposed system can be operated under two system modes: 1) starter generator system mode and 2) battery charging system mode, as shown in Table 1. Generally, the OBC and starter generator system are constructed in a normal HEV, separately. In order to construct these power conversion systems, the ratings of switch modules, gate drivers, and heat sinks etc. should be considered with regard to each system. Considering the rated power of normal OBC and starter generator system, a system volume of approximately 7.42 L is required. Also, the detailed system components and volume required to construct the power converter systems separately are shown in Table 2. On the other hand, the application of the proposed charging system results in the decrease in the system volume compared to the conventional HEVs. The reason is that the proposed charging system can operate as both conventional starter generator system mode and battery charging system mode. The proposed system utilizes only 8.8 kW rated power motor system and some power relays. The detailed system elements and its volume required to construct the integrated charging system is shown in Table 3. Despite of the using of additional power relays, due to the elimination of system components such as power stack and current sensors etc. to include conventional OBC, the overall system volume decreases by approximately 37%.

2.1 Starter Generator System Mode

The equivalent circuit configuration of the starter generator system mode is shown in Fig. 2. To construct the circuit for the starter generator system mode, three relays are turned on. Relay 1 is turned on to establish a connection between the vehicular battery and three-phase inverter. In this case, the DC-link capacitor is connected in parallel with the battery capacitor, thus, the equivalent capacitance $C_{Eq}$ is derived as follows:

$$C_{Eq} = C_{DC-link} + C_{Battery} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd -
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3 are turned on.

The circuit configuration and operation of the starter generator system mode is the same as the conventional starter generator system in HEVs. In particular, when HEVs are being driven in an urban area with frequent idling operations, the starter generator system functions as a traction motor, thereby reducing the pollutant emissions. In addition, when HEVs decelerate, the starter generator system transforms the kinetic energy into electrical energy and stores that energy in the battery to increase the system operation efficiency.

2.2 Battery Charging System Mode

As shown in the equivalent circuit configuration in Fig. 3, the circuit of the battery charging system mode consists of a single-phase grid system, filter inductor, full-bridge inverter, bi-directional DC–DC converter, and vehicular battery. To reconstruct the integrated on-board charging system as the battery charging mode, four power relays should be turned on. Relays 6 and 7 are turned on to connect the grid system with full-bridge inverter. In this topology, the AC power can be converted into DC power or vice versa through the operation of the full-bridge inverter. In addition, relays 4 and 5 are turned on to utilize the starter generator as a filter inductor for DC–DC converter. In other words, depending on the states of power relays, the role of the starter generator can be changed in the integrated on-board battery charging system. The equivalent inductance of the filter inductor in DC–DC converter is calculated as follows:

$$L_{eq} = L_c + \frac{L_a \times L_b}{L_a + L_b} \quad \cdots (2)$$

Where $L_a$, $L_b$, and $L_c$ represent the single winding of the starter generator. The equivalent circuit of the DC–DC converter is shown in Fig. 4.

In the battery charging system mode, only C-leg of three phase inverter is connected to winding of starter generator. When inverter outputs three phase voltage, only one active voltage vector is applied to the motor, i.e., the rotating magnetic field, which operates permanent magnetic synchronous motor (PMSM), is not generated. Thus, the winding of starter generator utilized only for filter inductor of DC–DC converter during battery charging system mode. As applying only one active voltage vector, noise or vibration generated by torque ripple is not occurred.

3. Control Method of Battery Charging System Mode

3.1 AC–DC Inverter

Fig. 5 shows the block diagram of the control of an AC–DC inverter. The proposed charging system utilizes only the single-phase grid system. Thus, only d-axis components can be derived when fulfilling the coordinate transform using the Clark’s transformation. In this study, an all pass filter (APF) is employed to generate q-axis components in the single-phase system. As shown in Fig. 6, an APF has a characteristic that only the phase of input signal is delayed while keeping the amplitude constant in selected frequency. The phase information about grid system is derived using the synchronous reference frame (SRF) phase locked loop (PLL) method.

The key role of an AC–DC inverter is to regulate the DC-link voltage depending on the reference voltage, constantly. In this paper, DC-link voltage is controlled by using a proportional-integral (PI) controller. The gain values of the controller are designed by modeling the DC-link capacitor using the following equations:

$$K_{p\text{AC}_{\text{vol}}} = \frac{2 \zeta C_{\text{DC–link}} \omega_{\text{AC}_{\text{vol}}}}{C_{\text{DC–link}} \omega_{\text{AC}_{\text{vol}}}} \quad \cdots (3)$$

$$K_{i\text{AC}_{\text{vol}}} = \frac{C_{\text{DC–link}} \omega_{\text{AC}_{\text{vol}}}}{C_{\text{DC–link}} \omega_{\text{AC}_{\text{vol}}}} \quad \cdots (4)$$

The duty ratio can be derived by using an output value of a DC-link voltage controller as a reference value for q-axis.
current controller. The proposed charging system utilizes the unipolar modulation switching method to reduce the current error and improve the total harmonic distortion (THD) of the output current in a steady state.

### 3.2 Multiple Harmonic Reduction Method

Generally, the harmonic currents can occur due to the operation of non-linear loads such as rectifiers and power converters. The distorted grid current due to harmonic components can decrease the system efficiency, cause vibration and noise in power converters, and premature ageing of system.

To reduce the 3rd harmonic current that is close to the fundamental frequency current, the non-ideal proportional resonant (PR) controller is applied using the following equation:

\[
\begin{align*}
    v_{gs,3rd}^* &= K_p \times i_{gs,3rd} - i_{3ds} \\
    &+ \frac{2K_r}{s^2 + 2\omega_c s + (\omega_0)^2} \times (i_{ds,3rd}^* - i_{3ds})
\end{align*}
\] (5)

Where \( K_p \) and \( K_r \) represent the proportional and resonant gain values of the controller, respectively. In addition, the bandwidth of the controller can be widened by setting \( \omega_c \).

As shown in Fig. 7, a non-ideal PR controller can regulate the specific frequency current selectively. In addition, it shows a better characteristic of the variation of current frequency compared to an ideal PR controller.

The harmonic components can be categorized as positive and negative sequence components in a three-phase grid system, as shown in Fig. 8. In other words, the value of each order harmonic component can be rotated as clockwise rotation or vice versa in stationary reference frame depending on the sequence of respective harmonic current. These differences are shown in following equations, which indicate harmonic current in phase sequence.

\[
\begin{align*}
    i_{d5th} &= I_5 \sin(5\omega_t + \theta) \\
    i_{q5th} &= -I_5 \cos(5\omega_t + \theta) \\
    i_{d7th} &= I_7 \sin(7\omega_t + \theta) \\
    i_{q7th} &= -I_7 \cos(7\omega_t + \theta)
\end{align*}
\] (6) (7)

The proposed charging system utilizes only the single-phase grid system, and thus, the categorization depending on the sequence is not allowed as in the three-phase system. For the regulation of harmonic currents such as 5th and
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Fig. 8. Variation of harmonics depending on the phase sequence

(a) Positive-sequence harmonics
(b) Negative-sequence harmonics

Fig. 9. Block diagram for the compensation of 5th and 7th harmonic currents

7th, a novel reduction technique is introduced, as shown in Fig. 9. The virtual q-axis components of 5th and 7th harmonics are generated in single-phase grid system to create the same phase sequence as in the three-phase grid system by using an APF. Through the coordinate transform utilizing the phase angle of the grid system, 5th and 7th harmonic components are converted into 6th harmonics in the synchronous reference frame. The transformed harmonics derived from 5th and 7th harmonic currents pass through APF to be controlled in the same way as fundamental current. In this case, the center frequency of APF is 300 Hz. To transform the target currents as DC values, each current is transformed to a value in the synchronous coordinate reference frame, which is rotated six times the angular velocity of the grid voltage. Except the DC components, total AC values are attenuated by passing through a low pass filter (LPF) to increase the performance of the harmonic current controller. The filtered 6th harmonics are utilized as input value to PI controller to reduce the harmonic currents.

The proposed 5th and 7th harmonic compensation method shows an advantage in the tuning process of the controller gain compared to the conventional 5th and 7th harmonic compensation method (26). Because the gain values to be adjusted by the user is reduced to half as compared to the conventional method, the controller design for harmonic reduction is further simplified.

3.3 Bidirectional DC–DC Converter

Fig. 10 shows the block diagram of the control of a bidirectional DC–DC converter. The block diagram consists of a battery voltage controller and DC–DC current controller that uses a PI controller. The gain values of the battery voltage controller can be derived by using the same modeling method as for the battery voltage controller. Like the AC–DC inverter, the DC–DC current controller utilizes the output of the voltage controller as a reference value. Moreover, the filter inductance of the DC–DC converter, the gain values of the DC–DC current controller can be modeled using the following equations:

\[
K_p^{DC\text{-cur}} = \frac{2}{\zeta L_{Eq} \omega_{DC\text{-cur}}}, \quad K_i^{DC\text{-cur}} = \frac{L_{Eq} \omega_{DC\text{-cur}}}{2}
\]  

(8)

Depending on the state of battery voltage, the control method of the DC–DC converter can be categorized into two modes: 1) constant current (CC) mode and 2) constant voltage (CV) mode. Before the battery voltage is charged to its nominal voltage, only the current controller is operated to adjust the battery charging current to a constant value through the CC mode. After the battery voltage reached to its nominal voltage, the control method is changed from CC to the CV mode. In other words, the voltage controller and current controller for DC–DC converter operate in combination depending on the reference voltage.
4. Simulation Results

The simulation works are implemented using the PSIM software to verify the effectiveness of the proposed circuit configuration and its control method. The simulation parameters are shown in Table 4. Considering the 2nd ripple of DC-link voltage, the capacitance is selected as 1000 μF. In addition, the filter inductance of the DC–DC converter is 0.9075 mH since the inductance of the single winding of the starter generator is 0.605 mH. The load resistor of the DC–DC converter is selected considering the rated power of the prototype of the integrated on-board battery charging system.

Fig. 11 shows the simulation waveforms of the DC-link voltage control. The DC-link voltage is changed from 400 V to 500 V for 0.1 s. The noticed point is observed when the battery voltage and current maintain a constant state regardless of the fluctuation of the DC-link voltage. From 0.6 s to 0.75 s, the battery voltage is controlled from 180 V to 360 V, as shown in Fig. 12. Due to the increase in the battery voltage, the battery current and grid current also increase from 9 A to 18 A and 7.8 Arms to 31.5 Arms, respectively. In addition, it can be confirmed through the analysis of Figs. 11 and 12 that the DC-link voltage and battery voltage are controlled independently.

Fig. 13 shows the performance of the proposed harmonic reduction method. When the proposed method is not applied, the THD of the grid current is approximately 23.6%. Furthermore, 3rd, 5th, and 7th harmonics include grid current of approximately 9.8 A, 2.0 A, and 0.8 A, as shown in Fig. 13(a). On the other hand, when the proposed method is applied, the THD of grid currents is improved by approximately 21.1%. Furthermore, each order harmonic is reduced under 0.2 A, as shown Fig. 13(b).

### Table 4. Simulation parameters

| Parameters                  | Value | Unit |
|-----------------------------|-------|------|
| Peak value of grid voltage  | 220   | V    |
| Frequency of grid voltage   | 60    | Hz   |
| Grid side inductance        | 2     | mH   |
| DC-link capacitance         | 1000  | μF   |
| Starter generator inductance| 0.605 | mH   |
| Battery capacitance         | 610   | μF   |
| Load resistance             | 20    | Ω    |
| Switching frequency         | 10    | kHz  |
| Sampling time               | 100   | μs   |

Fig. 11. Simulation waveforms of DC-link voltage control

Fig. 12. Simulation waveforms of battery voltage control

Fig. 13. Simulation waveforms of the multiple harmonic reduction method
5. Experiment Results

To verify the proposed theory, a prototype experimental set-up of rated power 6.5 kW was constructed. Also, the starter generator utilized in the integrated on-board battery charging system has an 8.8 kW rated power. The system configuration is shown Figs. 14(a), (b), respectively. This prototype was constructed using the SKM75GB12T4 module (made by Infineon) in consideration of the rating of the on-board charger system. The detailed parameters are same for simulation, as shown in Table 4.

Fig. 15 shows the experimental waveforms of the DC-link voltage control. The reference and actual DC-link voltage is changed from 400 V to 500 V. During the transient state of DC-link voltage, the grid and battery currents almost maintained their original state similar to the simulation results shown in Fig. 11.

The experimental results of the battery current control are shown Fig. 16. The transient state of battery current is approximately 0.6 s. In addition, the grid current changes with the battery current. When the battery current is controlled as 18 A, the peak value of the grid current is approximately 51 A. Furthermore, when the battery current is controlled as 9 A, the peak value of the grid current is approximately 14 A, which is similar to the simulation results shown in Fig. 12. As shown in Fig. 17, when the integrated on-board battery charger system operates as OBC mode, the power conversion efficiency is about 93.51% under the OBC rated power (6.6 kW).

Depending on the implementation of the proposed harmonic reduction method, experimental results are shown in Fig. 18. When the proposed method is not applied, as shown Fig. 17(a), the 3rd harmonic current contains the current of approximately 4 A, and 5th and 7th harmonics contain the current of approximately 0.5 A both. After the proposed compensation method is applied, each of the harmonics is reduced below 0.1 A, as shown in Fig. 17(b). Moreover, Fig. 19 shows the THD analysis results of the grid current according to the application of the proposed method by using the power analyzer WT 3000 (made by Yokogawa). After applying the proposed harmonic compensation method, the THD of the grid current reduces from 12.356% to 1.299%. Consequently, the proposed harmonic compensation method eliminates
low-order harmonics effectively, and its implementation and the tuning of the control gains are simpler than the conventional method that requires individual controller design for 5\textsuperscript{th} and 7\textsuperscript{th} harmonics.

6. Conclusions

In this paper, a multiple harmonic reduction method for the integrated on-board battery charging system of HEVs is presented. The proposed charging system can be operated in both starter generator system mode and OBC system mode by utilizing the existing power system and additional relays. In other words, the conventional power converter can be removed, and thus, the total system volume and weight of HEVs can be reduced. To improve the THD of the output current and system efficiency, the multiple harmonic compensation method is introduced. The proposed harmonic reduction method, particularly, in 5\textsuperscript{th} and 7\textsuperscript{th} harmonic current compensation method shows an advantage in terms of the selection of the gain value. The simulation results using PSIM software and experimental results employing a prototype of 6.5 kW verify the effectiveness of the proposed charging system and its control methods.

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References

(1) A. Emadi, Y.J. Lee, and K. Rajashekara: “Power electronics and motor drives in electric hybrid electric and plug-in hybrid electric vehicles”, IEEE Trans. Ind. Electron., Vol.55, No.6, pp.2237–2245 (2008)
(2) A.Y. Saber and G.K. Venayagamoorthy: “Plug-in vehicles and renewable energy sources for cost and emission reductions”, IEEE Trans. Ind. Electron., Vol.58, No.4, pp.1229–1238 (2011)
(3) A. Affanni, A. Bellini, G. Franceschini, P. Guglielmi, and C. Tassoni: “Battery Choice and Management for New-Generation Electric Vehicles”, IEEE Trans. Ind. Electron., Vol.52, No.5, pp.1343–1349 (2005)
(4) J. Moreno, M.E. Ortizar, and J.W. Dixon: “Energy-management system for a hybrid electric vehicle using ultracapacitors and neural networks”, IEEE Trans. Ind. Electron., Vol.53, No.2, pp.614–623 (2006)
(5) H.-G. Jeong and K.-B. Lee: “Controller design for a quick charger system suitable for electric vehicles”, J. Electr. Eng. Technol., Vol.8, No.5, pp.1122–1130 (2013)
(6) F.R. Salmasi: “Control Strategies for Hybrid Electric Vehicle: Evolution Classification Comparison and Future Trends”, IEEE Trans. Veh. Technol., Vol.56, No.3, pp.2393–2404 (2007)
(7) Y. Bak, E. Lee, and K.-B. Lee: “Indirect Matrix Converter for Hybrid Electric Vehicle Application with Three-Phase and Single-Phase Outputs”, Energies, Vol.8, No.5, pp.3849–3866 (2015)
(8) A. Emadi, K. Rajashekara, S.S. Williamson, and S.M. Lukic: “Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations”, IEEE Trans. Veh. Technol., Vol.54, No.3, pp.763–770 (2005)
(9) C. Shi, Y. Tang, and A. Khaligh: “A three-phase integrated onboard charger for plug-in electric vehicles”, IEEE Trans. Power Electron., Vol.33, No.6, pp.4716–4725 (2018)
(10) S. Haghiin, S. Lundmark, M. Alakula, and O. Carlson: “An isolated high-power integrated charger in electrified vehicle applications”, IEEE Trans. Veh. Technol., Vol.60, No.9, pp.4115–4126 (2011)
(11) Y. Lee, A. Khaligh, and A. Emadi: “Advanced Integrated Bi-directional AC/DC and DC/DC Converter for Plug-in Hybrid Electric Vehicles”, IEEE Trans. Veh. Technol., Vol.58, No.3, pp.3970–3980 (2009)
(12) S. Haghiin, K. Khan, S. Zhao, M. Alakula, S. Lundmark, and O. Carlson: “An integrated 204 kW motor drive and isolated battery charger for plug-in vehicles”, IEEE Trans. Power Electron., Vol.28, No.8, pp.4013–4029 (2013)
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