

Article

Dynamic Characteristic Improvement of Integrated On-Board Charger Using a Model Predictive Control

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Abstract: This paper proposes a dynamic characteristic improvement of an integrated on-board charger (OBC) using a model predictive control (MPC) method. The integrated OBC performs both battery charging and starter generator (SG) driving for engine starting in plug-in hybrid electric vehicles (PHEVs). If it performs battery charging, battery-side voltage and battery-side current are control objects which are usually controlled by using a proportional-integral (PI) controller. However, it has the disadvantage of undesirable dynamic characteristics, and gain tuning of the PI controller is necessary to properly control the voltage and current. Therefore, this paper proposes the MPC method for the dynamic characteristic improvement of integrated OBC. It can achieve not only dynamic characteristic improvement, but also robustness from the abrupt change of load impedance. By using the proposed MPC method for integrated OBC, the settling time to control the output voltage is decreased by 50% in the transient state compared to that by using the PI controller. The effectiveness of the proposed MPC method is verified by simulation and experimental results.

Keywords: plug-in hybrid electric vehicle; on-board charger; model predictive control method; dynamic characteristic improvement



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1. Introduction

With the increasing demand for environmental regulations and carbon dioxide reduction in response to the awareness of global warming and fossil fuel depletion, research on electric vehicles (EVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs) has been globally proceeded. These vehicles can replace internal combustion engine vehicles regarding high driving efficiency and low exhaust emission [1–5]. In particular, research on PHEVs has been conducted with various subjects such as electric motor, on-board charger (OBC), and starter generator (SG).

The electric motor is necessary for PHEV propulsion [6–8] and the OBC is used for battery charging of PHEV by connecting the grid source in the household [9–11]. The SG with drive inverter is used for engine starting from an idle stop, which increases the driving efficiency of PHEV. Its role is primarily classified into two parts. Firstly, it converts mechanical energy such as kinetic energy into electrical energy for battery charging. Secondly, it relieves exhaust emission when PHEV is stopped for a moment [12–18].

In general, PHEV has the OBC and the SG with drive inverter, which are composed of each power conversion system separately. It causes a problem with increasing the number of components, weight, and volume of PHEV. To solve this problem, recently, research on integrated OBC has progressed [19–23]. In [19–21], integrated OBC performs battery charging by utilizing the windings of the SG as a filter inductor of the grid source. However, it requires complicated control and operation method of integrated OBC for battery charging. In [22,23], the windings of the SG are used as the inductor of a DC-DC converter. The integrated OBC is constructed by removing the conventional OBC from PHEV and installing an additional circuit in the SG with drive inverter to utilize the

windings of the SG. As a result, the integrated OBC can perform both battery charging and SG driving for engine starting.

When the integrated OBC performs battery charging, battery-side voltage and battery-side current are control objects which are usually controlled by using a proportional-integral (PI) controller due to its simplicity of implementation and intuitiveness [24]. However, it has the disadvantage of undesirable dynamic characteristics, and gain tuning of the PI controller is necessary to properly control the voltage and current. The proportional gain is related to the dynamic characteristic improvement of integrated OBC in the transient state and the integral gain is related to reducing the error of the voltage and current in a steady state. It has a limitation in increasing the gain of the PI controller. If the gain is increased for the dynamic characteristic improvement of integrated OBC, an overshoot of the voltage and current can occur [25–27]. In [25–27], the optimization design method of the PI controller used a binary-coded extremal optimization (BCEO) algorithm and stationary frame equivalent model of the PI controller.

To overcome these disadvantages of the PI controller, a model predictive control (MPC) method can be used for integrated OBC. Before micro controller unit (MCU) technology was developed, the MPC method was hard to use for industrial systems due to problems with high computation burden. However, recently, research on the MPC method has been actively conducted with the development of MCU technology [28,29]. In the MPC method, generally, an optimal control input can be obtained by minimizing a cost function designed by modeling the control system and by predicting the next state of the control target in the control system. As a result, the control system using the MPC method can improve dynamic characteristics and it does not require a control loop or modulator to control the system compared with that using the PI controller.

Therefore, this paper proposes the MPC method for the dynamic characteristic improvement of integrated OBC without an overshoot of battery-side current. In the proposed MPC method, the battery-side current can be controlled by using duty ratio as optimal control input with the modeling of integrated OBC. In addition, when an abrupt change of load impedance is occurred, a compensation method of the battery-side voltage ripple using a power feed-forward component is also proposed. As a result, the proposed MPC method can achieve not only dynamic characteristic improvement, but also robustness from an abrupt change of load impedance. The effectiveness of the proposed MPC method for integrated OBC is verified by simulation and experimental results.

2. Circuit Configuration and Operation Principle of Integrated OBC

2.1. Circuit Configuration

Figure 1 shows the circuit configuration of integrated OBC, which is constructed by installing relays (R_1 – R_7), a filter inductor (L_f), a single-phase grid source, and an additional circuit in the SG with drive inverter. In addition, it is composed of switches of three-leg (S_{Ap} , S_{An} , S_{Bp} , S_{Bn} , S_{Cp} , and S_{Cn}), DC-link capacitor (C_{DC}), battery side capacitor (C_{bat}), and the SG. Although integrated OBC demands the installation of additional components, it realistically decreases the number of components, weight, and volume of PHEV compared with that having the OBC and the SG with drive inverter separately because the volume for IGBT modules, gate drivers, and heatsink used in the integrated OBC is considerably decreased [19–23].

As listed in Table 1, the quantity and volume of the main elements required to compose each power conversion device for the OBC and the SG in the conventional PHEV are about 22 EA and 7.42 L, respectively. On the other hand, the number of main elements in integrated OBC is 21 EA. It is not significantly different compared with that of the conventional PHEV because R_1 – R_7 are added. Although R_1 – R_7 are added in integrated OBC, the volume of them is about 0.27 L and it does not considerably affect the volume of integrated OBC. However, since the volume for IGBT modules, gate drivers, and heatsink used in the integrated OBC is considerably decreased, the volume required to compose integrated OBC is decreased up to 4.65 L, which is about 37% smaller. As a result, integrated

OBC can decrease the volume of PHEV by reducing the number of main elements occupying a large volume.

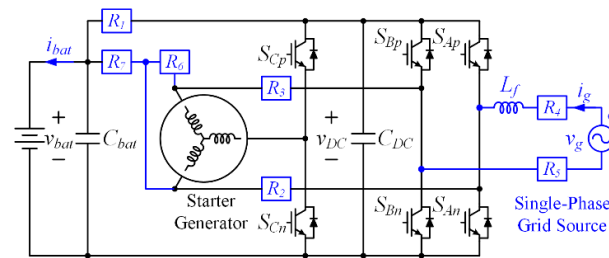


Figure 1. Circuit configuration of integrated OBC.

Table 1. Comparison of main elements quantity and volume in HEV.

Main Elements	Quantity (EA) and Volume (L)			
	Separated OBC and SGS		Integrated OBC	
IGBT modules	6	0.59	3	0.29
gate drivers	2	0.26	1	0.13
grid filter inductors	1	0.19	1	0.19
DC-link capacitors	4	0.84	4	0.84
battery side capacitors	1	0.22	1	0.22
current sensors	6	0.22	3	0.11
heatsink	2	5.10	1	2.60
power relays	-	-	7	0.27
total	22	7.42	21	4.65

The integrated OBC can perform both battery charging and SG driving by modifying its circuit depending on state of R_1 – R_7 . Above all, when R_1 – R_3 are turn-off and R_4 – R_7 are turn-on, the integrated OBC performs battery charging. Figure 2 shows the simplified circuit configuration of integrated OBC which performs battery charging. It is mainly divided into a full-bridge converter and a buck converter. The full-bridge converter regulates DC-link voltage (v_{DC}) constantly from the single-phase grid source and the buck converter regulates battery-side voltage (v_{bat}) and current (i_{bat}) from a DC-link.

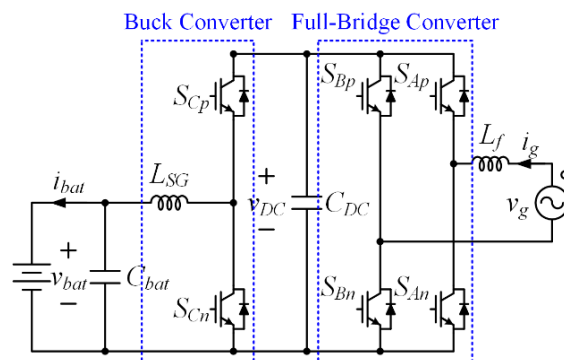


Figure 2. Simplified circuit configuration of integrated OBC which performs battery charging.

Additionally, since the windings of the SG are used as the inductor of the buck converter, an equivalent inductance (L_{SG}) of the inductor is 1.5 times compared with that of the single-winding of the SG.

2.2. Operation Principle

In the full-bridge converter, leg-A and leg-B are operated independently and not only switches of leg-A (S_{Ap} and S_{An}), but also switches of leg-B (S_{Bp} and S_{Bn}), have complementary switching states, respectively. The duty ratio of them is determined by control of v_{DC} and grid-side current (i_g). As a result, the operation of the full-bridge converter makes v_{DC} as DC value from the grid-side voltage (v_g) as the AC value, and it is capable of power factor correction (PFC) of the single-phase grid source.

Additionally, in the buck converter, switches of leg-C (S_{Cp} and S_{Cn}) have complementary switching states. The duty ratio of them is determined by control of v_{bat} and i_{bat} . As a result, the operation of the buck converter performs battery charging from the DC-link.

Figure 3 shows the equivalent operation circuit of the buck converter which performs battery charging; however, a resistive load is considered by replacing a battery connected to the buck converter in this paper. It is divided into two different modes. In mode 1, as shown in Figure 3a, S_{Cp} , as an upper switch of leg-C, is the ON state and S_{Cn} , as a lower switch of leg-C, is the OFF state because they have complementary switching states. Therefore, inductor voltage (v_L) is expressed as in (1) by Kirchhoff's voltage law (KVL) and inductor current (i_L) is increased because v_L is positive.

$$v_{L,1} = v_{DC} - v_{out}, \quad \frac{di_{L,1}}{dt} = \frac{v_{L,1}}{L_{SG}} = \frac{v_{DC} - v_{out}}{L_{SG}}, \quad (1)$$

where v_{out} is the output voltage. Contrastively, in mode 2, as shown in Figure 3b, S_{Cp} is OFF state and S_{Cn} is ON state. The v_L is expressed as in (2) and i_L is decreased because v_L is negative:

$$v_{L,2} = -v_{out}, \quad \frac{di_{L,2}}{dt} = \frac{v_{L,2}}{L_{SG}} = \frac{-v_{out}}{L_{SG}}. \quad (2)$$

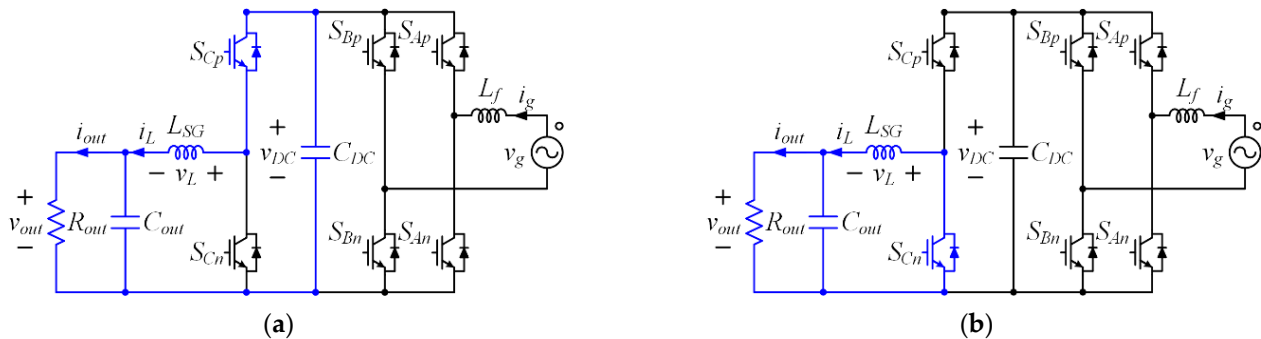


Figure 3. Equivalent operation circuit of buck converter which performs battery charging: (a) mode 1; (b) mode 2.

Applying the voltage-second balance to v_L , a voltage transfer ratio of the buck converter is calculated as in (3):

$$\begin{aligned} \frac{v_{DC} - v_{out}}{L_{SG}} \cdot DT_s &= \frac{v_{out}}{L_{SG}} \cdot (1 - D)T_s, \\ v_{DC} \cdot DT_s - v_{out} \cdot DT_s &= v_{out} \cdot T_s - v_{out} \cdot DT_s, \quad \frac{v_{out}}{v_{DC}} = D, \end{aligned} \quad (3)$$

where D is the duty ratio and T_s is the control period.

Figure 4 shows the inductor voltage and current waveforms depending on the switching state of integrated OBC. Firstly, each leg of the full-bridge converter composed of S_{Ap} , S_{An} , S_{Bp} , and S_{Bn} is independently operated with a duty ratio determined by control of v_{DC} and i_g . Secondly, the operation of the buck converter can be divided into two modes, as shown in Figure 3, depending on the switching state of S_{Cp} and S_{Cn} . The S_{Cp} is ON state

during T_1 in mode 1 and the S_{Cn} is ON state during T_2 in mode 2. Additionally, T_1 and T_2 are determined by D as in (4):

$$T_1 = DT_s, \quad T_2 = (1 - D)T_s. \quad (4)$$

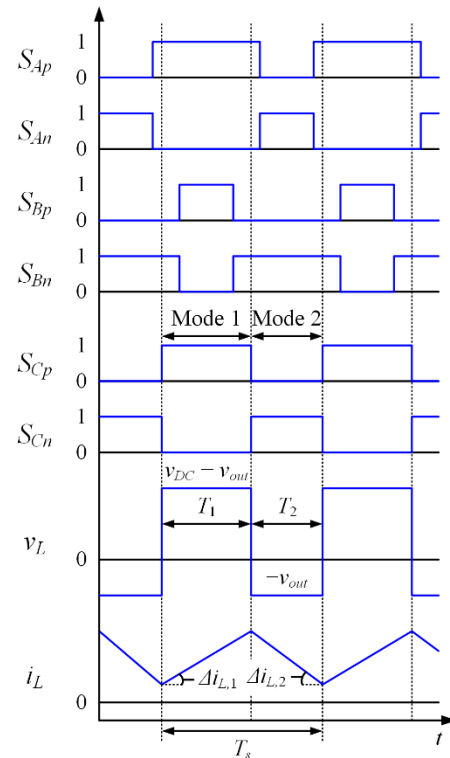


Figure 4. Inductor voltage and current waveforms depending on switching state of integrated OBC.

In mode 1, i_L increases by $\Delta i_{L,1}$ during T_1 because v_L is positive as in (1). Contrastively, in mode 2, i_L decreases by $\Delta i_{L,2}$ during T_2 because v_L is negative as in (2).

3. Model Predictive Control Method of Integrated OBC

3.1. Predictive Model Establishment

Figure 5 shows the circuit configuration of integrated OBC for the predictive model establishment. Firstly, applying Kirchhoff's current law in node D, as shown in Figure 5, i_L is expressed as in (5).

$$i_L = i_{out} + i_C, \quad (5)$$

where i_{out} is the output current and i_C is the capacitor current, which is expressed as in (6):

$$i_C = C_{out} \frac{dv_{out}}{dt}, \quad (6)$$

where C_{out} is the output capacitance. Substituting (6) into (5), the variation of v_{out} is calculated as in (7):

$$\begin{aligned} i_L &= i_{out} + C_{out} \frac{dv_{out}}{dt}, \quad \frac{dv_{out}}{dt} = \frac{\Delta v_{out}}{T_s} = \frac{1}{C_{out}} (i_L - i_{out}), \\ \Delta v_{out} &= \frac{T_s}{C_{out}} (i_L - i_{out}) = \frac{T_s}{C_{out}} \left(i_L - \frac{v_{out}}{Z_L} \right), \end{aligned} \quad (7)$$

where Z_L is the impedance of the resistive load and Δv_{out} in (7) can be expressed as in (8):

$$\Delta v_{out} \cong v_{out(k)} - v_{out(k-1)} = \frac{T_s}{C_{out}} \left(i_L - \frac{v_{out}}{Z_L} \right), \quad (8)$$

where $v_{out(k)}$ and $v_{out(k-1)}$ are the present and the previous state of v_{out} , respectively. From (8), Z_L is calculated as in (9) and it can be used to calculate i_{out} or i_C as in (10):

$$Z_L = \frac{v_{out}}{i_L - \frac{C_{out}}{T_s}(v_{out(k)} - v_{out(k-1)})}, \quad (9)$$

$$i_{out} = \frac{v_{out}}{Z_L}, \quad i_C = i_L - i_{out} = i_L - \frac{v_{out}}{Z_L}. \quad (10)$$

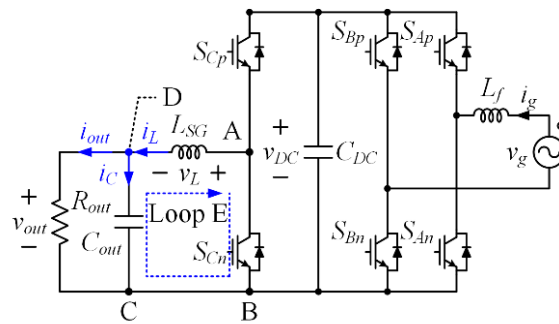


Figure 5. Circuit configuration of integrated OBC for predictive model establishment.

Secondly, applying the KVL in loop E connected with node A, B, C, and D, as shown in Figure 5, a voltage between node A and B (v_{AB}) is expressed as in (11):

$$v_{AB} = v_{out} + v_L. \quad (11)$$

Since v_L is expressed as in (12), substituting (12) into (11), the variation of i_L is calculated as in (13):

$$v_L = L_{SG} \frac{di_L}{dt}, \quad (12)$$

$$v_{AB} = v_{out} + L_{SG} \frac{di_L}{dt}, \quad \frac{di_L}{dt} = \frac{\Delta i_L}{T_s} = \frac{1}{L_{SG}}(v_{AB} - v_{out}), \quad (13)$$

$$\Delta i_L = \frac{T_s}{L_{SG}}(v_{AB} - v_{out}).$$

In (13), v_{AB} is divided as in (14) depending on the switching state of the buck converter as shown in Figure 3:

$$v_{AB} = \begin{cases} v_{DC} & \text{at Mode 1} \\ 0 & \text{at Mode 2} \end{cases} \quad (14)$$

Therefore, substituting (14) into (13) and using (4), Δi_L is calculated as in (15):

$$\Delta i_{L,1} = \frac{T_1}{L_{SG}}(v_{DC} - v_{out}) = \frac{DT_s}{L_{SG}}(v_{DC} - v_{out}), \quad (15)$$

$$\Delta i_{L,2} = \frac{T_2}{L_{SG}}(0 - v_{out}) = \frac{(1-D)T_s}{L_{SG}}(0 - v_{out}),$$

where $\Delta i_{L,1}$ is the increased amount of i_L in mode 1 during T_1 and $\Delta i_{L,2}$ is the decreased amount of i_L in mode 2 during T_2 .

3.2. Control Method for Full-Bridge Converter

Figure 6 shows the control block diagram for the full-bridge converter of integrated OBC which performs battery charging. It is mainly classified into DC-link voltage controller, single-phase grid source current controller, and third-harmonic reduction [30]. The v_{DC} is controlled to reference DC-link voltage (v_{DC}^*) using the voltage controller, and the d - q axis currents (i_d and i_q) are controlled to reference d - q axis current (i_d^* and i_q^*) using the current controller, respectively. In addition, i_d^* is set to zero for a unit power factor control of the single-phase grid source. The non-ideal proportional-resonant (PR) controller in third-harmonic reduction is suitable to reduce the third-harmonic component included

in i_g , which is close to the fundamental component of i_g , because it has narrow frequency bandwidth [31]. As a result, the full-bridge converter of integrated OBC performs AC-DC power conversion between the single-phase grid source and the DC-link.

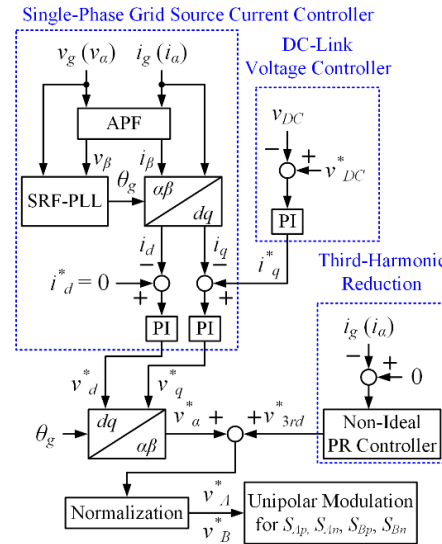


Figure 6. Control block diagram for full-bridge converter of integrated OBC which performs battery charging.

3.3. Proposed Model Predictive Control Method

Figure 7 shows the control block diagram for the proposed MPC method. Firstly, in an output voltage controller based on the PI controller, v_{out} as the output voltage of integrated OBC is controlled to reference output voltage (v_{out}^*) as the control object. The output of the PI controller is reference inductor current (i_L^*), which is used to calculate reference output power with v_{out}^* as in (16).

$$P_{out}^* = v_{out}^* i_L^*. \quad (16)$$

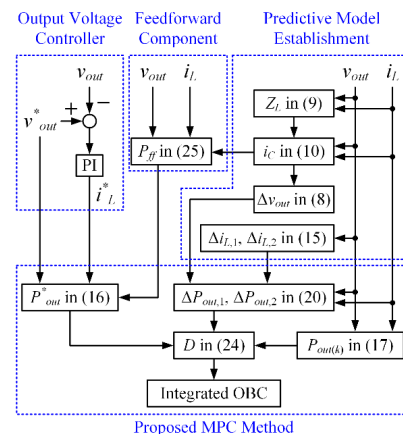


Figure 7. Control block diagram for the proposed MPC method.

Secondly, Z_L , i_c , Δv_{out} , $\Delta i_{L,1}$, and $\Delta i_{L,2}$ are calculated by using the predictive model establishment. Finally, through the proposed MPC method, D as the duty ratio of integrated OBC is obtained. Its detailed explanations are as follows.

First, a present state output power of integrated OBC is expressed as in (17):

$$P_{out(k)} = v_{out} i_L. \quad (17)$$

From (17), by using Δv_{out} and Δi_L , which are calculated as in (8) and (13), a next state output power of integrated OBC can be predicted as in (18):

$$\begin{aligned} P_{out(k+1)} &= (v_{out} + \Delta v_{out})(i_L + \Delta i_L) \\ &= v_{out}i_L + v_{out}\Delta i_L + \Delta v_{out}i_L + \Delta v_{out}\Delta i_L. \end{aligned} \quad (18)$$

From (17) and (18), the variation of output power (P_{out}) of integrated OBC is calculated as in (19):

$$\begin{aligned} \Delta P_{out} &= P_{out(k+1)} - P_{out(k)} \\ &= (v_{out}i_L + v_{out}\Delta i_L + \Delta v_{out}i_L + \Delta v_{out}\Delta i_L) - (v_{out}i_L) \\ &= v_{out}\Delta i_L + \Delta v_{out}i_L + \Delta v_{out}\Delta i_L. \end{aligned} \quad (19)$$

From (19), by using $\Delta i_{L,1}$ and $\Delta i_{L,2}$ as in (15), the slope of P_{out} is expressed as in (20):

$$\begin{aligned} \Delta P_{out,1} &= (v_{out}\Delta i_{L,1} + \Delta v_{out}i_L + \Delta v_{out}\Delta i_{L,1})/T_1, \\ \Delta P_{out,2} &= (v_{out}\Delta i_{L,2} + \Delta v_{out}i_L + \Delta v_{out}\Delta i_{L,2})/T_2, \end{aligned} \quad (20)$$

where $\Delta P_{out,1}$ is the increasing slope of P_{out} in mode 1 during T_1 , and $\Delta P_{out,2}$ is the decreasing slope of P_{out} in mode 2 during T_2 . From (19) and (20), $P_{out(k+1)}$ is expressed as in (21):

$$\begin{aligned} P_{out(k+1)} &= P_{out(k)} + \Delta P_{out} \\ &= P_{out(k)} + T_1\Delta P_{out,1} + T_2\Delta P_{out,2} \\ &= P_{out(k)} + DT_s\Delta P_{out,1} + (1-D)T_s\Delta P_{out,2}. \end{aligned} \quad (21)$$

As a result, the cost function in the proposed MPC method is defined as in (22) as the error of P_{out} :

$$\begin{aligned} P_{err} &= P_{out}^* - P_{out(k+1)} \\ &= P_{out}^* - P_{out(k)} - DT_s\Delta P_{out,1} - (1-D)T_s\Delta P_{out,2}. \end{aligned} \quad (22)$$

If v_{out} is properly controlled to v_{out}^* as the control object, P_{err} as the cost function is set to zero. Therefore, the cost function as in (22) is expressed as in (23):

$$\begin{aligned} P_{out}^* - P_{out(k)} &= DT_s\Delta P_{out,1} + (1-D)T_s\Delta P_{out,2} \\ &= DT_s\Delta P_{out,1} + T_s\Delta P_{out,2} - DT_s\Delta P_{out,2} \\ &= DT_s(\Delta P_{out,1} - \Delta P_{out,2}) + T_s\Delta P_{out,2}. \end{aligned} \quad (23)$$

From (23), as a result, D as the duty ratio for the next state of integrated OBC is calculated as in (24):

$$D = \frac{P_{out}^* - P_{out(k)} - T_s\Delta P_{out,2}}{T_s(\Delta P_{out,1} - \Delta P_{out,2})}. \quad (24)$$

Finally, depending on D calculated as in (24), the switching state of S_{Cp} and S_{Cn} are determined as shown in Figure 4.

Additionally, the ripple component of v_{out} occurs when the load impedance is abruptly changed. It should be compensated because it deteriorates the dynamic characteristic and reliability of integrated OBC. Therefore, a feedforward component of output power as in (25) is added to P_{out}^* to compensate abrupt change of load impedance:

$$P_{ff} = v_{out}(i_L - i_C). \quad (25)$$

4. Simulation Results

The effectiveness of the proposed MPC method for integrated OBC as shown in Figure 5 is verified by PSIM simulation. The simulation parameters are listed in Table 2.

Table 2. Simulation parameters.

Parameters	Value
single-phase grid source (v_g)	220 V _{rms} /60 Hz
filter inductance (L_f)	4 mH
DC-link capacitance (C_{DC})	2000 μ F
single-winding inductance	0.605 mH
equivalent inductance (L_{SG})	0.9075 mH
output capacitance (C_{out})	610 μ F
output resistance (R_{out})	20 Ω
control period (T_s)	100 μ s

Figure 8 shows the simulation results of operation principles depending on the switching state of integrated OBC when v_{out} is controlled to 140 V as shown in Figure 8f. Figure 8a,b indicate the switching state of S_{Ap} , S_{An} , S_{Bp} , and S_{Bn} of the full-bridge converter, which is determined by control of v_{DC} and i_g . Figure 8c indicates the switching state of S_{Cp} and S_{Cn} of the buck converter, which is determined by control of v_{out} with the proposed MPC method. Figure 8d indicates v_L , which is determined as positive or negative depending on the switching state of S_{Cp} and S_{Cn} . Finally, i_L , as shown in Figure 8e, increases or decreases depending on v_L .

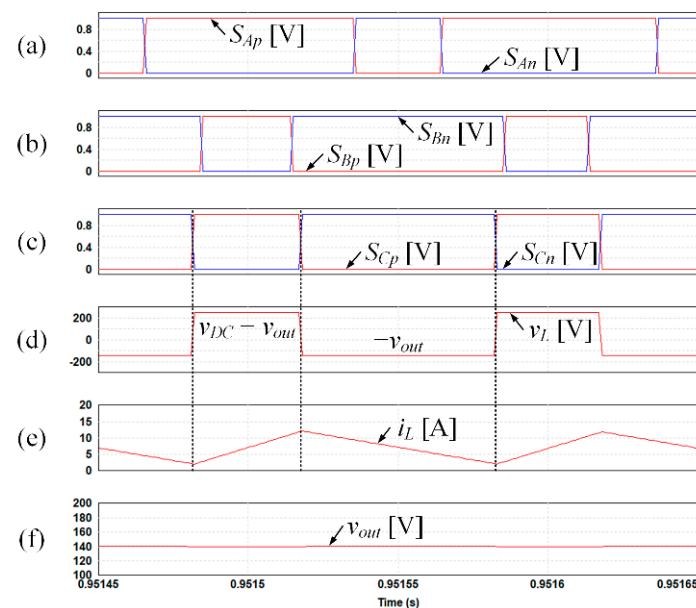


Figure 8. Simulation results of operation principles depending on switching state of integrated OBC: (a) operation state of S_{AP} and S_{An} , (b) operation state of S_{Bp} and S_{Bn} , (c) operation state of S_{Cp} and S_{Bn} , (d) inductor voltage, (e) inductor current, and (f) output voltage.

Figure 9 shows the simulation results of integrated OBC which performs battery charging. Figure 9a,b indicate v_g and i_g . In addition, v_g is set to 220 V_{rms}/60 Hz. Figure 9c,d indicate v_{DC} and v_{out} , respectively. The v_{DC} is controlled to v_{DC}^* , which is set to 400 V, using the full-bridge converter. Additionally, the v_{out} is controlled to v_{out}^* , which is set to 140 V, using the buck converter. In Figure 9c, a fluctuation of v_{DC} as the second-harmonic component is generated by the full-bridge converter with the single-phase grid source. It can be decreased by using a reduction technique with the PR controller and feedforward compensation [32,33]; however, it is not considered in this paper.

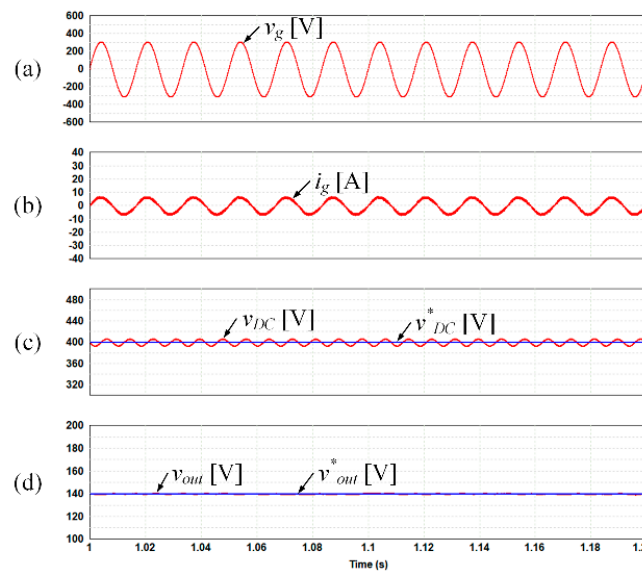


Figure 9. Simulation results of integrated OBC which performs battery charging: (a) voltage and (b) current of the single-phase grid source, (c) DC-link voltage and reference DC-link voltage, and (d) output voltage and reference output voltage.

Figure 10 shows the simulation results of output voltage control of integrated OBC using (a) PI control and (b) the proposed MPC method. It indicates i_L , D , v_{out} , and v_{out}^* , which is changed to 160 V from 80 V at 0.8 s. In Figure 10a, the v_{out} of integrated OBC is controlled to v_{out}^* using the PI control, and the settling time to reach 160 V is approximately 80 ms in the transient state. If the gain of the PI controller is increased for the dynamic characteristic improvement of integrated OBC, the control of integrated OBC will become unstable [25–27]. Therefore, the bandwidth of the output voltage controller based on the PI controller was set to 1/40 times of the switching frequency and the bandwidth of the output current controller was set to 1/5 times of the bandwidth of the output voltage controller. In Figure 10b, the gain of the output voltage controller based on the PI control is identical to that in Figure 10a and the v_{out} of the integrated OBC is controlled to v_{out}^* using the proposed MPC method. The settling time to reach 160 V is approximately 45 ms in the transient state. Compared with that in Figure 10a, the dynamic characteristic improvement of integrated OBC is achieved by using the proposed MPC method.

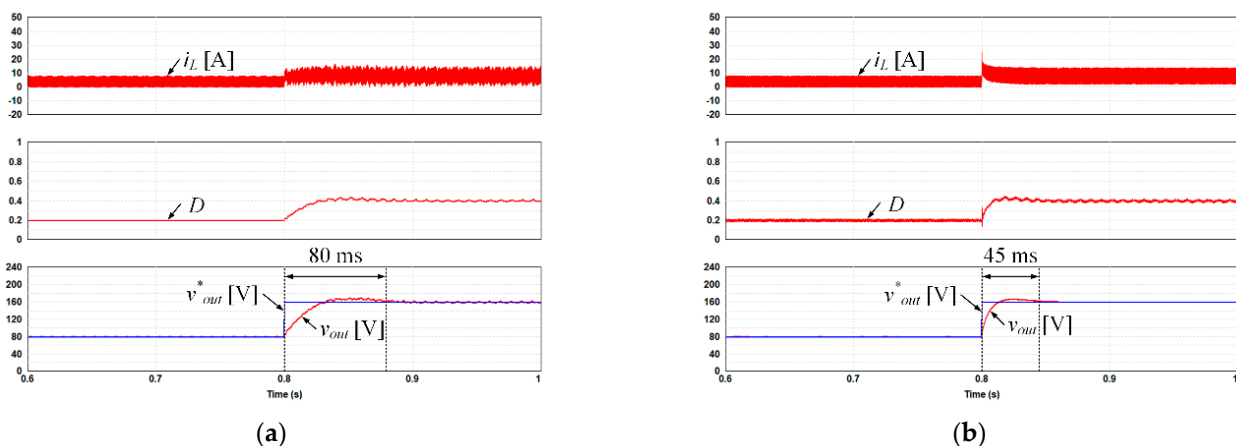


Figure 10. Simulation results of output voltage control of integrated OBC using (a) PI control and (b) the proposed MPC method.

Figure 11 shows the simulation results of output voltage control of integrated OBC using the proposed MPC method. It indicates v_{DC} , v_{DC}^* , i_L , v_{out} , and v_{out}^* , which are changed to 160 V from 80 V at 0.8 s and to 100 V from 160 V at 1.0 s. The v_{out} of integrated OBC is controlled to v_{out}^* using the proposed MPC method and the robustness of the proposed MPC method is verified by simulation results.

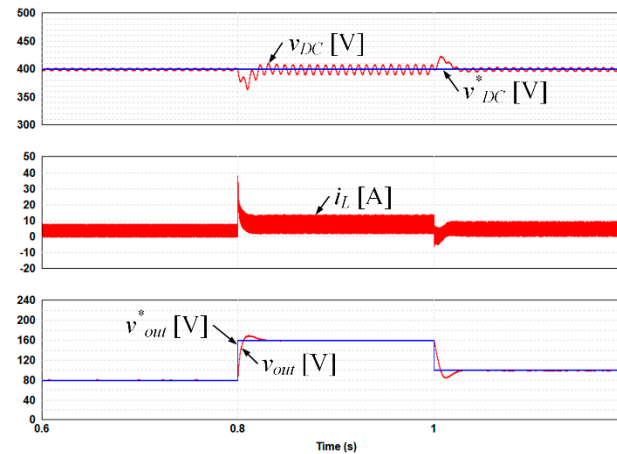


Figure 11. Simulation results of output voltage control of integrated OBC using the proposed MPC method.

Figure 12 shows the simulation results of output voltage control of integrated OBC when the load impedance is abruptly changed (a) without a feedforward component of output power and (b) with a feedforward component of output power. It indicates i_L , P_{out} , v_{out} , and v_{out}^* , which are set to 160 V. The v_{out} of integrated OBC is controlled to v_{out}^* using the proposed MPC method and the load impedance is abruptly changed to 20 Ω from 40 Ω at 1.2 s. In Figure 12a, v_{out} fluctuates greatly when the load impedance is abruptly changed. However, in Figure 12b, v_{out} does not fluctuate, although the load impedance is abruptly changed because the feedforward component of output power is applied to the proposed MPC method.

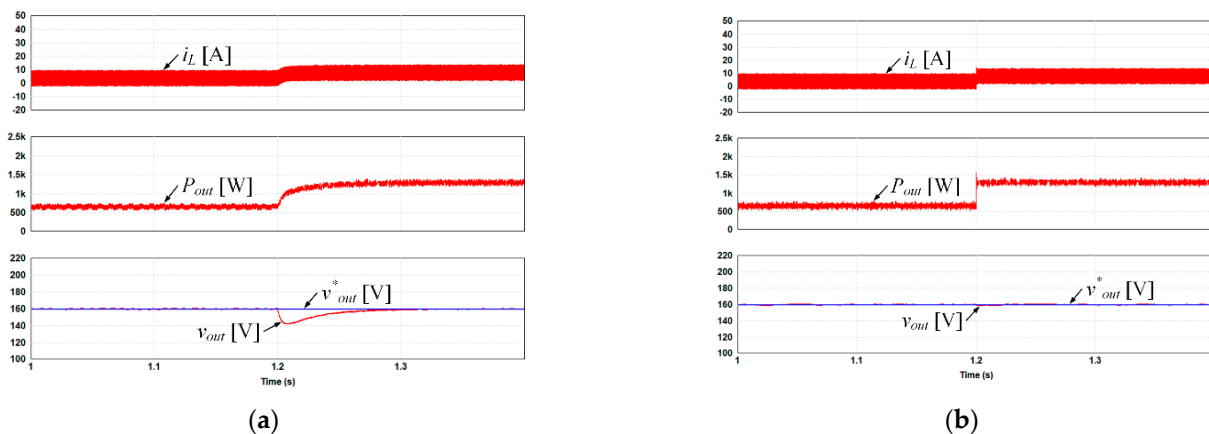


Figure 12. Simulation results of output voltage control of integrated OBC when the load impedance is abruptly changed (a) without a feedforward component of output power and (b) with a feedforward component of output power.

5. Experimental Results

The experiments were performed to verify the effectiveness of the proposed MPC method for integrated OBC. Figure 13 shows the experimental setup, which is composed of a control board with a digital signal processor (DSP) using the TMS320F28335, fans, relays,

and switches. The IGBT modules are designed by SKM75GB12T4 (1200 V/75 A) from Semikron considering v_{DC} of 400 V as the DC-link voltage. The experimental parameters were identical to those of the simulation as listed in Table 2. However, to extend the power ranges for a real HEV/PHEV, not only the inductance and capacitance of elements comprising the experimental setup, but also the rated voltage and current of devices, should be increased considering the detailed specification of integrated OBC for a real HEV/PHEV.

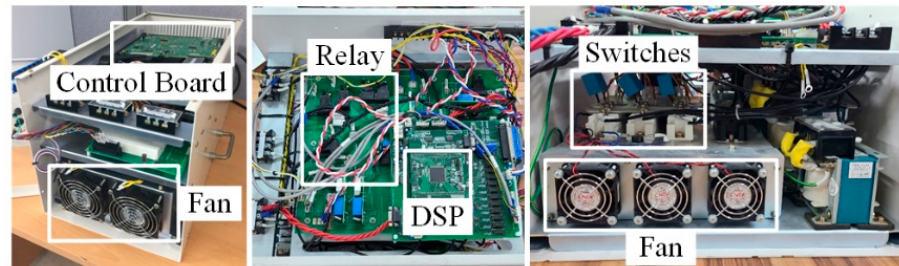


Figure 13. Experimental setup.

Figure 14 shows the experimental results of integrated OBC which performs battery charging. The v_g is set to 220 V_{rms}/60 Hz and v_{DC} is controlled to 400 V using the full-bridge converter. Additionally, unit power factor control of the single-phase grid source is performed, and the third-harmonic component included in i_g is reduced by the non-ideal PR controller as shown in the FFT spectrum in Figure 14. Since the power factor of the single-phase grid source and harmonic components are affected by the control of the full-bridge converter, the power quality of the grid side is not influenced by the PI controller and the proposed MPC method. Finally, the v_{out} is controlled to 160 V using the buck converter.

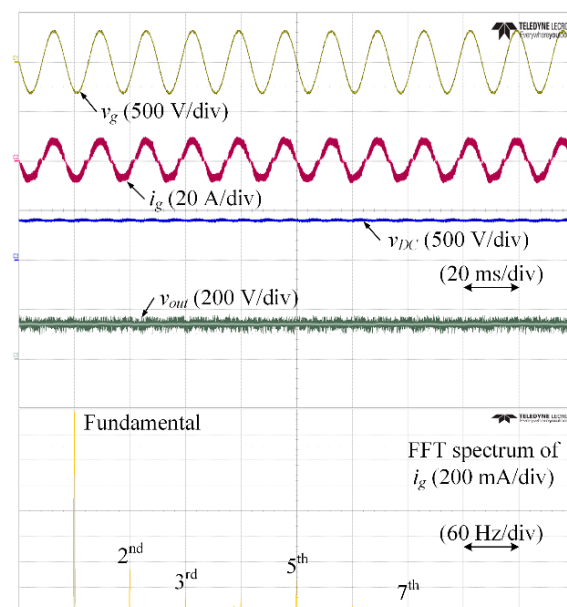


Figure 14. Experimental results of integrated OBC which performs battery charging.

Figure 15 shows the experimental results of output voltage control of integrated OBC using (a) PI control and (b) the proposed MPC method. The v_{out}^* is changed to 160 V from 80 V; additionally, it is changed to 80 V from 160 V. In Figure 15a, v_{out} is controlled to v_{out}^* using the PI control and the settling time to reach 160 V is approximately 112 ms in the transient state. In Figure 15b, v_{out} is controlled to v_{out}^* using the proposed MPC method and the settling time to reach 160 V is approximately 50 ms in the transient state. As a result,

compared with that in Figure 15a, the dynamic characteristic improvement of integrated OBC is achieved by using the proposed MPC method. Additionally, in the simulation and experimental results using the proposed MPC method, as shown in Figures 10 and 14, the settling time to control the output voltage is decreased by 50% in the transient state compared to that by using the PI controller. In other words, the performance of the dynamic characteristic improvement of the proposed MPC method in the experimental results is similar to that in the simulation results. Moreover, the dynamic characteristic performance of the proposed MPC method is desirable compared with the performance of the MPC method in [34–38].

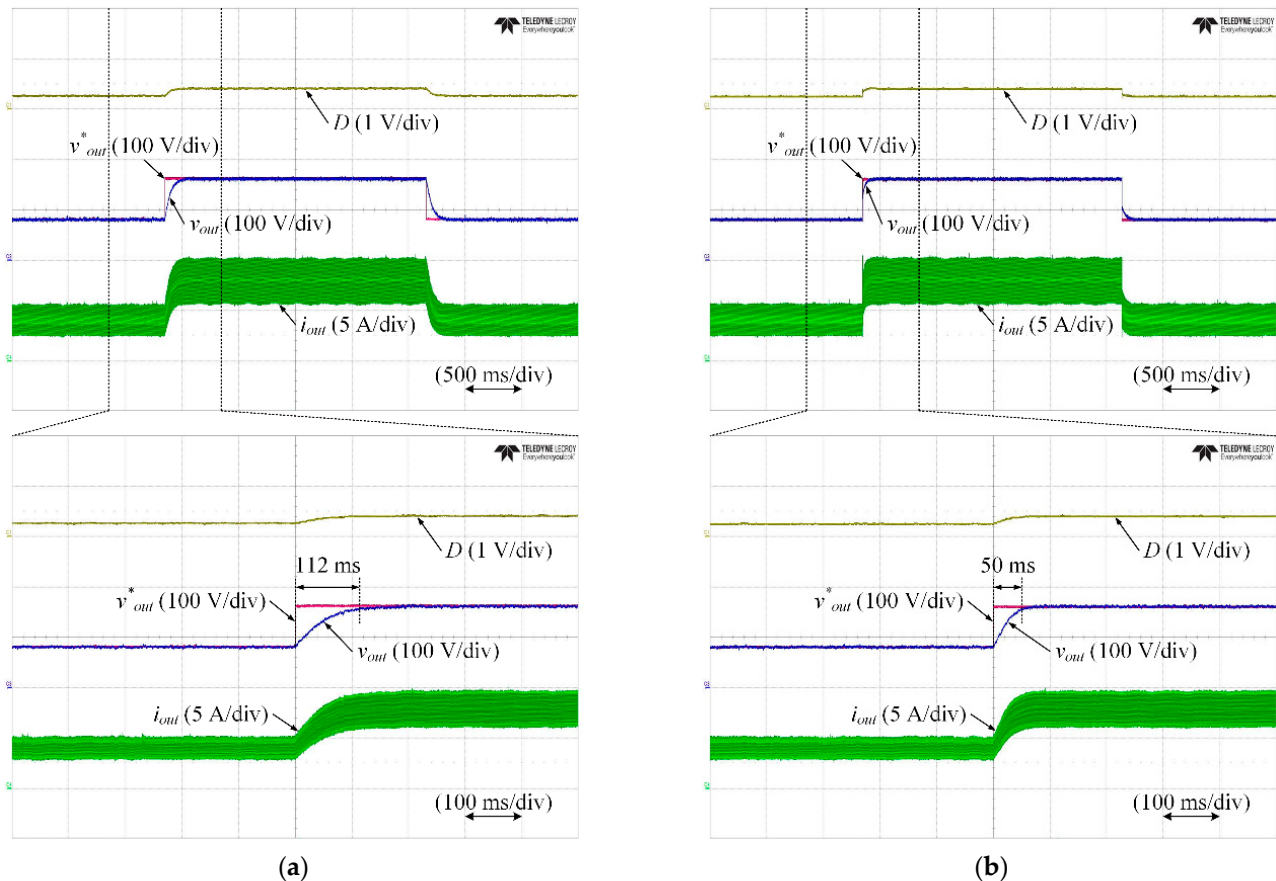


Figure 15. Experimental results of output voltage control of integrated OBC using (a) PI control and (b) the proposed MPC method.

Figure 16 shows the experimental results of output voltage control of integrated OBC when the load impedance is abruptly changed (a) without a feedforward component of output power and (b) with a feedforward component of output power. The v_{out} is controlled to v_{out}^* , which is set to 160 V, using the proposed MPC method and the load impedance is abruptly changed to 20 Ω from 40 Ω . The v_{out} fluctuates greatly when the load impedance is abruptly changed in Figure 16a; however, the v_{out} does not fluctuate, although the load impedance is abruptly changed because the feedforward component of output power is applied to the proposed MPC method in Figure 16b.

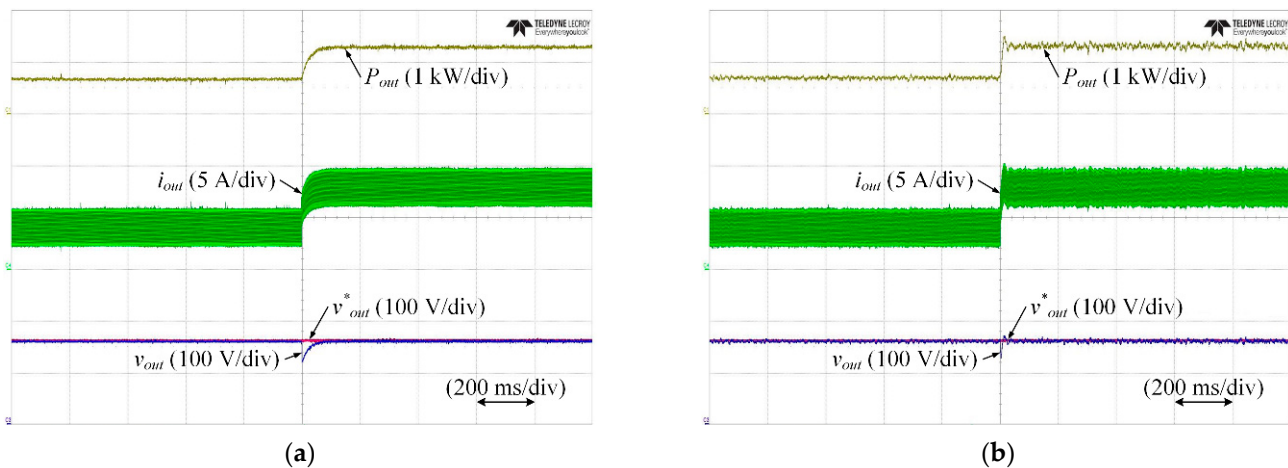


Figure 16. Experimental results of output voltage control of integrated OBC when the load impedance is abruptly changed (a) without a feedforward component of output power and (b) with a feedforward component of output power.

6. Conclusions

This paper proposed the dynamic characteristic improvement of an integrated OBC which performs battery charging using the MPC method. Other MPC methods for EV chargers improve the dynamic characteristics of the DC-link voltage, not output voltage, using the inherent relationship between the DC-link voltage reference and the active power reference. However, in this paper, the proposed MPC method improves the dynamic characteristics of the output voltage using a variation of output power based on the predictive model establishment of integrated OBC, and the duty ratio is determined in the direction of minimizing the cost function. As a result, it can achieve not only dynamic characteristic improvement, but also robustness from an abrupt change of load impedance of the integrated OBC. The effectiveness of the proposed MPC method of the integrated OBC is verified by simulation and experimental results.

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