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Research Paper



Model-based predictive control of dc-dc converter for EV applications

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Abstract

Background/Objectives: The power performance of electric vehicle chargers depends on the control efficiency of the power converters with on-board and off-board types. In this paper, a new control method is proposed for power converter of fast electric vehicle chargers in order to improve the power efficiency.
Methods/Statistical analysis: The proposed control method is the optimal control to minimize the performance objectives from the predicted output, based on the system model. The discretized model of DC-DC converter with sampling time is derived by using lifting operation for taking into account with the desired prediction time.
Findings: The existing conventional controllers are obtained by off-line optimal solution and applied to the systems. Once the control gain is determined, the controller is able to reflect the system response at the real-time.
Improvements/Applications: The proposed control method has advantages to deal with system performances at real-time and the control actuation is updated every sampling time via the derived mathematical model. It can be directly applicable to real electric vehicle charger systems in industry.

Keywords: *MPC; EV Charger; DC-DC Converter; Optimal Control; Off-Board EV Charger*

1. Introduction

Recently, electric vehicle (EV) has been increasingly paid attention for their various advantages such as maintenance cost, driving price, green energy, governments support, and so on [1]. The infrastructure for the more revitalization of the EV markets is necessary such as exclusive parking place, many charging stations, cost down of the vehicles, continuous research [2].
Especially, the electric charger systems are fundamental technology for EV systems because the efficiency of the charging is directly related to purchasing power of the EV. EV charging systems is focused on with not only the viewpoint of vehicles, but the power supply from vehicle to grid and home, called V2G and V2H, respectively[2, 3]. For the V2G and V2H technologies require the performance improvement of the power converter such that the power converter produces the stable power voltage and current to save the power efficiency.
The structures of the power converter for V2G and V2H depend on the type of EV charger such and fast-charger and slow-charger [4]. The technology of the fast charger is more important in industry due to their applicability and business. The fast EV charger contains various power converters, AC-DC rectifier, DC-DC converter, and DC-AC inverter in the cars 4. In this paper, the control method for DC-DC converter is dealt with to produce the stable performance and improved efficiency. For the V2G and V2H, the bidirectional power converter is required to convert and transfer the power each other [5].
Generally, proportional and integral (PI) control is implemented for voltage and current control to avoid the steady state error and stable performance. DC-DC converter switching is controlled every controlling time with respect to the feedback of the measured voltage and current by sensors. AC-DC converter [6-8] should discretize using microprocessor, the measured voltage and current outputs.
For the EV battery charging, the common charging converters are controlled for practically constant current (CC) and constant voltage (CV) charging. In this paper, we focus on the development of controller design for CV of DC-DC power converter in order to maintain a constant voltage level via model-based optimal control method. The proposed control method predicts the future response from mathematical model, and the control input is determined in order to minimize the cost including the time and stability performances [9].
The main contributions of the proposed model-based optimal control are summarized as follows.

i). The proposed model-based control method improves the existing PI control without any additional resources to measure outputs with fast sampling compensator.
ii). The robust stability and noise rejection are simultaneously guaranteed with optimal control method.
iii). The various input-to-output time responses can be additionally considered by the proposed MPC approach.

This paper is organized as follows. In Section II, the fundamentals of DC-DC converter for EV charger systems are introduced. Section III discusses the proposed control method from the mathematical model of the bidirectional DC-DC converter. The effectiveness and efficiency of the developed method is shown by simulation results in Section IV. Finally, the conclusion of the paper is explained in Section V.

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2. Power converter for fast EV charger system

The general structure of EV power converter systems is shown in figure 1. In the EV and EV charger system include the AC-DC, DC-DC, and DC-AC power converters [10].

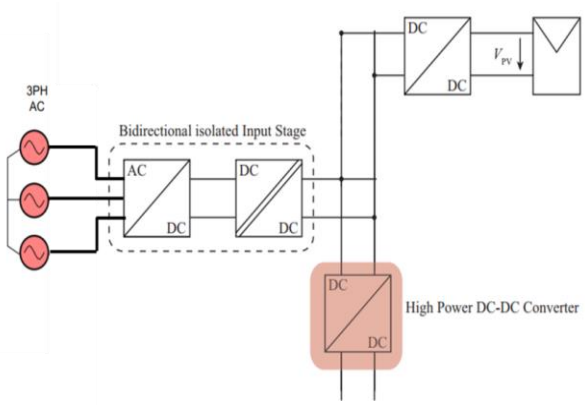


Fig. 1: General Structure of Power Converters for EV Charger and Grid.

The isolated DC-DC power converter controls DC link voltage 200~800V by AC-DC converter to DC battery voltages, 12V. For AC-DC rectifier, various formulations are applied in industry, such as Vienna, active front end rectifier, and so on.
Figure 2 shows the structure of power converters and controller for off-board EV charger. The off-board EV charger contains AC-DC, DC-DC converter, and controller to switch the legs of converters. The controller for EV charger controls the front and end DC voltages of the DC-DC converter.

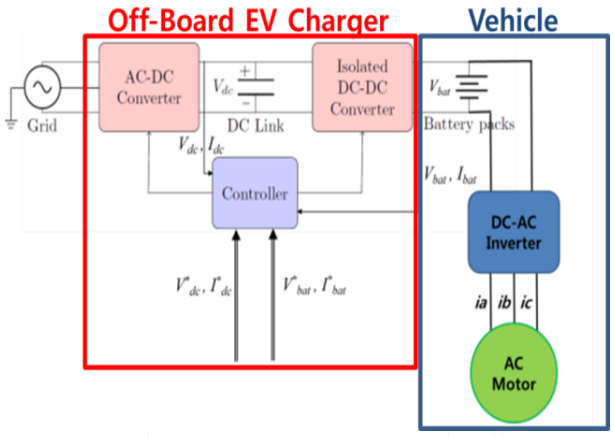


Fig. 2: Structure of Power Converters and Controller for Off-Board EV Charger.

In this paper, the control method of the bidirectional and isolated DC-DC converter is dealt with, shown in figure 2. The general DC-DC converter is modeled second order state-space linear system. For EV charger, reference DC voltage link and reference battery charging voltage are 400V and 12V, respectively. The DC voltage link for EV charger is between 200V and 800V with respect to the EV charger standard, such as cHAdeMo, Combo 1, and so on.
In this paper, we select 400V for the Combo 1 type and the 3-phase 380V commercial voltage is considered in the electricity standard of Korea.

3. MPC for DC-DC converter

In this paper, we propose model-based predictive control method for DC-DC controller. Figure 3 shows the structure of proposed model-based predictive controller for DC-DC converter. Different from general PI controller for DC-DC converter, the proposed controller predicts the future current and voltage responses by mathematical model of the converter.

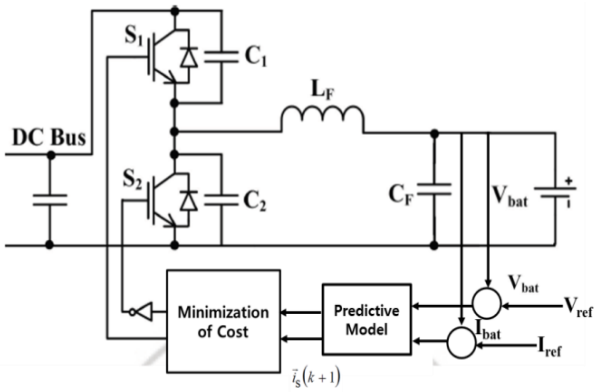


Fig. 3. Structure of Proposed Model-based Predictive Controller for DC-DC Converter.

The mathematical model of the DC-DC converter is obtained from the voltage and current structure in figure 3 as equation 1.

$$\begin{bmatrix} \frac{di(t)}{dt} \\ \frac{du_o(t)}{dt} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_F} & -\frac{1}{L_F} \\ \frac{T_s}{C_F} & 1-\frac{T_s}{RC_F} \end{bmatrix} \begin{bmatrix} i(k) \\ u_o(k) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L_F} \\ 0 \end{bmatrix} u_i(k)S \quad (1)$$

Where R , L_F, C_F are represented as the transfer resistance, inductor and capacitor of circuit for battery. S is the switching factor between buck and boost mode of DC-DC converter [11], [12].
The switching factor can be modified as the element of the system matrix as equation 2.
The switching factor can be modified as the element of the system matrix as equation 2.

[■ ((di (t))/dt@ (du_o (t))/dt¬)]=[■ (1&-1/L_F (1-S)@1/C_F (1-S)&-1/(RC_F))][■(i(t)@u_o (t)¬)]+[■(1/L_F @0¬)] u_i (k) (2)

The derived mathematic model equation (1) and (2) are discretized as equation (3) and (4), respectively. The model-based predictive control method uses the discrete time systems and the recent DC-DC converter for PWM module 12.

$$\begin{bmatrix} i(k+1) \\ u_o(k+1)\neg \end{bmatrix} = \begin{bmatrix} 1 & \frac{T_s}{L_F} \\ \frac{T_s}{C_F} & 1-\frac{T_s}{RC_F} \end{bmatrix} \begin{bmatrix} i(k) \\ u_o(k)\neg \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L_F} \\ 0\neg \end{bmatrix} u_i(k)S \quad (3)$$

$$\begin{bmatrix} i(k+1) \\ u_o(k+1)\neg \end{bmatrix} = \begin{bmatrix} 1 & -\frac{T_s}{L_F(1-S)} \\ \frac{T_s}{C_F(1-S)} & 1-\frac{T_s}{RC_F} \end{bmatrix} \begin{bmatrix} i(k) \\ u_o(k)\neg \end{bmatrix} + \quad (4)$$

The derived discrete model is sampled at the single sampling time in equation (3) and (4). Let T_s be the slow sampling rates for the actuators and sensors, respectively. The sampling time can be rearranged as $t = T_s k$ with $k = 0, 1, \ldots n$.
The predicted output and states are extended as additional states from equation (3) and (4) by lifting operation in order to predict the all future time as equation (5) 13.

$$\begin{bmatrix} x(k+1) \\ x(k+2) \\ \vdots \\ x(k+n) \end{bmatrix} = \begin{bmatrix} \Phi \\ \Phi^2 \\ \vdots \\ \Phi^N \end{bmatrix} x(k) + \begin{bmatrix} \Phi^0 & 0 & \cdots & 0 \\ \Phi^0 & \Phi^1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \Phi^0 & \Phi^1 & \cdots & \Phi^{n-1} \end{bmatrix} B \begin{bmatrix} u_i(k) \\ u_i(k+1) \\ \vdots \\ u_i(k+n) \end{bmatrix} \quad (5)$$

$$\begin{aligned} x(k+1,0) &= \Phi^{R_m} x(k,0) + \tilde{\Gamma}_u \tilde{u}(k) \\ \tilde{y}(k,0) &= C_y x(k,0) + \tilde{D}_{yu} \tilde{u}(k) \end{aligned} \quad (6)$$

Where

$$\Phi = e^{AT_i} \quad , \quad \Gamma = \int_0^{T_i} e^{A(T_i-\theta)} dtB,$$

$$\tilde{\Gamma}_u = \begin{bmatrix} \Phi^{R_m-1}\Gamma_u & \Phi^{R_m-2}\Gamma_u & \cdots & \Gamma_u \end{bmatrix}$$

$$\tilde{C}_z = \begin{bmatrix} C_z \\ C_z\Phi \\ \vdots \\ C_z\Phi^{R_m-1} \end{bmatrix}, \tilde{D}_{yu} = \begin{bmatrix} D_{yu} & 0 & \cdots & 0 \end{bmatrix},$$

$$\tilde{z}(k) = \begin{bmatrix} z(k,0) \\ z(k,1) \\ \vdots \\ z(k,R_m-1) \end{bmatrix}, \tilde{u}(k) = \begin{bmatrix} \tilde{u}(k,0) \\ \tilde{u}(k,1) \\ \vdots \\ \tilde{u}(k,R_m-1) \end{bmatrix}$$

The proposed controller determines the PWM switching signal to minimize the cost function of performance index with respect to the predicted states by the lifting operation and input states by equation (6) and (7). We propose the new cost function equation (8) in order to consider the current states and control inputs. To minimize the control input improves the efficiency of DC-DC converter.

$$g = \sum_{n=1}^{N} \lambda_{1n} |i^*(k+n) - i(k+n)| + \lambda_{2n} |u_o^*(k+n) - u_o(k+n)| \quad (8)$$

The optimal design procedure of model-based predictive controller for DC-DC power converter of EV fast charger is summarized below and figure 4.

Step 1. Find a linearized and discretized mathematical model P(s) of nonlinear buck-boost DC-DC bidirectional power converter, given circuit parameters with passive elements.

Step 2. Specify appropriate cost functions to consider performance and robustness with input and output states.

Step 3. Set a generalized single rate discrete time plant T (z) with molel-based controller by lifting operator.

Step 4. Determine the optimal control switching to minimize cost function for the single-rate sampled data system in slow sample period by solving the optimization problem shown as equation (8)

Step 5. Check the response of the closed loop system, then return to the step 2 if it is unsatisfactory.

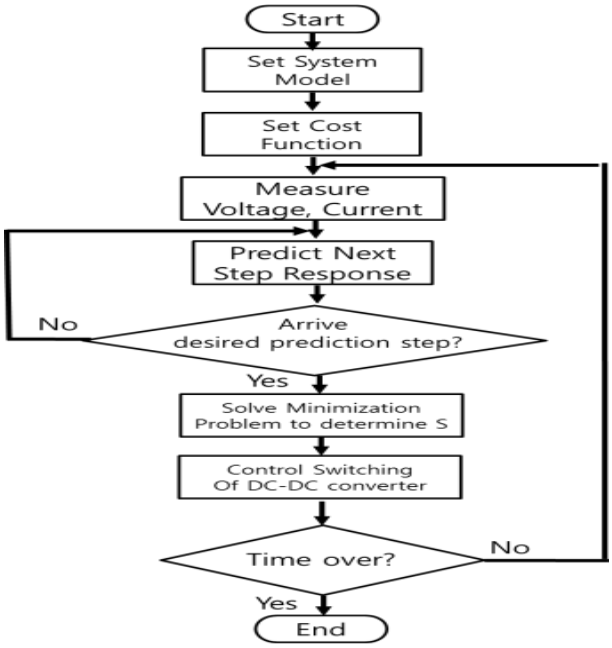
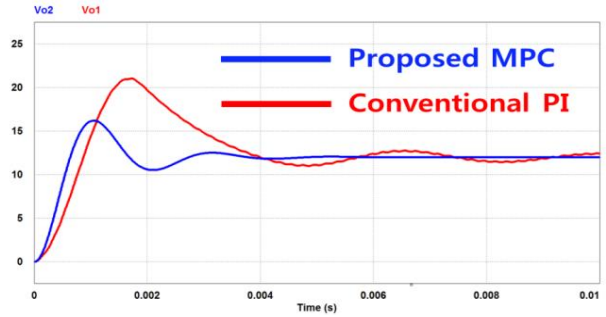


Fig. 4: The Proposed Control Procedure of Model-Based Predictive Controller.

4. Simulation

The simulation is performed by PSIM program software to show the effectiveness of the proposed control method. The reference DC voltage link is 400V and EV charging battery voltage is 12V. The time domain performances such as the rising time, settling time, and overshoot of the proposed control input produces the better than the conventional PI control in figure 5.



Fi. 5: Simulation Results for the Comparison of Model-Based Predictive Control with Conventional PI Control.

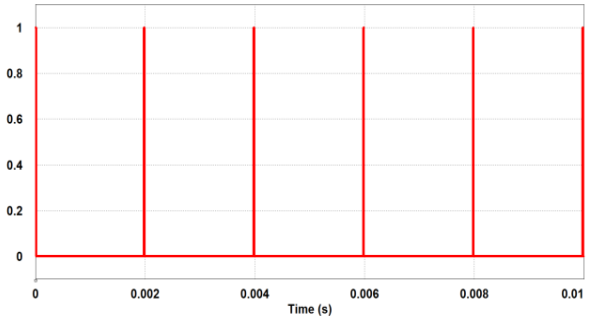


Fig. 6: Switching Signal of the DC-DC Converter Controlled by the Proposed Control Method.

The figure 6 shows the switching signal of S1 switch of DC-DC converter in figure 3. The switching signal is determined every actuating time with respect to the sampling time Ts. The faster sampling and switching time is applied, the better performance is produced. The switching signal is zero or one as like figure (6).

5. Conclusion

This paper proposed an improved control method for DC-DC converter of fast EV charger via model-based predictive control. The proposed controller can consider the future time input and output responses predicted by derived systems model with lifting operation. The control factor, shown as switch signal in DC-DC converter, is determined by solving the optimization problem subject to the constraints and performance index represented by input and output states. The proposed control method not only maintains the robust stability performance of the linear quadratic optimal control, but also produces the better time domain performance such as rising and settling time and overshoot than the conventional PI control method. The effectiveness of the proposed method is illustrated by simulations. The applicability of the proposed control method is expected for the real EV systems in industry.

Acknowledgment

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