

LQ-PI Controller Design for Multi-Phase Interleaved DC/DC Converter

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Abstract

Background/Objectives: Generally, the performance of multi-phase interleaved DC/DC Converter requires the system to be controlled by a power semiconductor with a rated capacity smaller than the conventional converter because the output load current is distributed. However, the controller design of a power semiconductor for the converter is intricate and complicated. In this paper, we propose the optimal control techniques in order to minimize the stress of converters and improve the time response and performance of the controlled system.

Methods/Statistical analysis: The proposed control method is to determine the weighting factors of the optimal linear quadratic-proportional integral control in order to meet the specifications of the controlled response, ensuring the internal stability. The mathematical model of the multi-phase interleaved DC/DC Converter is derived using a transfer function according to the relation between input current and output voltage.

Findings: The proposed controller has the characteristics of a simpler and improved frequency domain loop shapes than conventional optimal control techniques that achieve internal stability and meet design specifications for good command followings and disturbance reduction against sensor noises and modelling errors.

Improvements/Applications: The proposed control method has the advantage to improve the performance of multi-phase interleaved DC/DC converter and guarantee the internal stability and robustness of the controlled response based on the derived mathematical model. The proposed design process is simple and applicable to various industries such as renewable energy and fast charge system for electric vehicles.

Keywords: Linear Quadratic-Proportional Integral Control, Multi-phase DC/DC Converter, Optimal Control, internal Stability

1. Introduction

Multi-phase interleaved DC/DC converters are widely used in power conversion devices such as power supply, power compensation unit, uninterruptible power supply (UPS), and so on because of the high efficiency and applicability of this converter. Especially, the multi-phase interleaved DC/DC converter is applicable to battery storage system of renewable energy systems, electric vehicles, electric vehicle charging systems, and vehicle to grid power systems for the good power factor and noise rejection properties [1, 2, 3, 4].

For the electric vehicle systems or grid connected systems, the reduction of current ripple and the effect of sensor noise for current and voltage should be importantly dealt with because these systems are directly connected to each main power grid and vehicles with passengers. In addition, the multi-phase interleaved DC/DC converter is operated by the semiconductor switches with a lower rated capacity than the conventional DC/DC converter because the load current is distributed to each phase [5,6]. Therefore, the control of the multi-phase switching is one of the most important factors for the power efficiency and quality of the converted voltages. Interleaved method for controlling multi-phase DC/DC converter reduces the capacity of a ripple current by multiplying current and decreasing the phase difference of the

current flow. These advantages can be used to minimize the stress on circuit elements such as inductors, switches and capacitors such that the controlled power systems and battery management systems are improved in durability and stability of the systems [7,8].

In this paper, we develop a mathematical model for an interleaved multi-phase DC / DC converter as the transfer function model with respect to input to output voltages including current states. The developed control method has the structure of the improved proportional-integral (PI) control based on the linear quadratic (LQ) optimization method. The proposed LQ-PI method is determined in order to satisfy concurrently the internal stability and the required performance in time and frequency domains of the multi-phase DC / DC converter. Control gain factors are finally tuned by solving Riccati equation of optimal LQ regulator problems for the performance and stability of the individual components in the converter. The effectiveness of the proposed control method is shown by the simulation results.

2. Multi-Phase Interleaved DC/DC Converters

The multi-phase interleaved DC/DC Converter consists of input output power circuits, switching filters, and controller, as shown in Figure 1. This converter has the advantages in the capacity of the inductor and the rated voltage and current of the power

semiconductor, which requires the smaller capacities than conventional single-phase interleaved DC/DC converters. Shown in Figure 1, the three-phase system is selected for modeling and control, and the phase of the interleaved converter switch is determined based on the characteristics of the system [11].

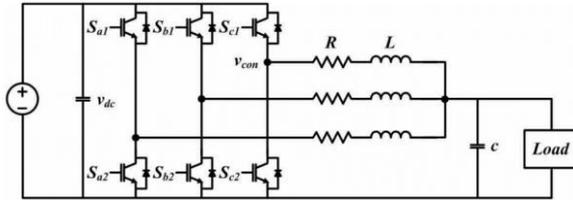


Figure 1: Topology of the Three-phase DC/DC Converter

Interleaved three-phase architecture improves overall system efficiency by reducing the ripple current in the output, and reduces the capacity and volume of power devices. The size of the ripple current in the output decreases by one-third compared to the single-phase converter and the three-phase converter. Since the signal from an electric semiconductor is a three-phase system, each switch operates in an on-off manner as shown in Figure 2.

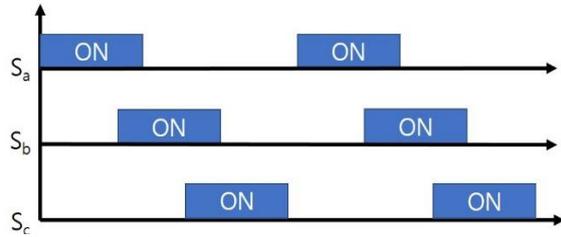


Figure 2: Time Chart of Interleaved Three-phase Switching

Output current of the converter with respect to the each phase is three times higher in frequency than conventional single-phase converters such that the current ripple can be reduced. Interleaved switching operating process is sequentially as shown in Figure 2. Because each phase has the electric angle difference of 120° , the power width modulation switching to the power gate occurs in the each time zone. This switching interleaved process provides the effect of offsetting the output ripple voltage as well as three phases of current. The interleaved converter types have many advantages differently from the conventional single configuration converters. The converter requires high inductance at low switching frequencies, but with interleaved converters the distribution of current in each phase allows the design of low-capacity inductance and capacitance. And since the 3 phase current is superimposed, the switching frequency effect is three times higher than the single phase converter.

3. Mathematical Model and Controller Design

3.1. Mathematical Model of the Converter

Interleaved multi-phase DC/DC converter for the EV charger systems consists of switches, inductors, and I/O capacitors in which the output voltage is mathematically expressed as eq. (1) using S_{on} with respect to a switching state.

$$V_{con} = S_{on} V_{dc} \quad (1)$$

where V_{dc} is the converter output voltage, S_{on} is a switching state to represent 1 and 0 according to on and off of switch. The state equation of the converter is shown as eq. (2).

$$V_{out} = L \frac{di_x}{dt} + Ri_x + V_{con} \quad (2)$$

where $i_x(t)$ is the phase current, L is the filter inductance and R is the resistance component. The derivative of the output current is represented from eq. (2) as shown in eq. (3).

$$\frac{di_x}{dt} = \frac{1}{L} (V_{out} - Ri_x - V_{con}) = \frac{\Delta i_x}{t_s} \quad (3)$$

where Δi_x is the differential in output current and t_s is the control period time. The input current of the output capacitor is expressed as eq. (4).

$$i_c = c \frac{dV_{out}}{dt} \quad (4)$$

where i_c is the capacitor input current and c represents the capacity of the output capacitor. The derivative of the output voltage from eq. (4) is shown in eq. (5).

$$\frac{dv}{dt} = \frac{1}{c} i_c = \frac{1}{c} \left(i_c - \frac{V_{out}}{z} \right) = \frac{\Delta V_{out}}{t_s} \quad (5)$$

where z is the load impedance of the output, and ΔV_{out} is the differential in output voltage. Finally, mathematical differential equation of the load impedance values is derived as discontinues state equation shown in eq. (6) and eq. (7).

$$V_{out(k)} - V_{out(k-1)} = \frac{t_s}{c} \left(i_{c(k)} - \frac{V_{out(k)}}{z(k)} \right) \quad (6)$$

$$z(k) = \frac{V_{out(k)}}{i_{c(k)} - \frac{c}{t_s} (V_{out(k)} - V_{out(k-1)})} \quad (7)$$

3.2. Proposed Controller Design

LQ regulator optimal controller has a structure with state feedback but the error signal cannot be dealt with such that the regulator is not proper for the servo control systems to consider error to be zero. In this paper, LQ servo controller is improved by including the output variable as a new state in order to follow the reference command for the tracking performance. By defining a state variable as containing an output variable, the state space model can be expressed as shown in eq. (8).

$$\begin{cases} dx_p(t) = A_p x_p(t) + B_p u(t) & , x_p(t) \in R^2 \\ y(t) = C_p(t) & , y(t) \in R^1 \end{cases} \quad (8)$$

To match a PID structure to LQR control system, we augment the integral part of the output variable to the feedback loop as a state variable, as shown in eq. (9), and make it as the description state [10].

$$x(t) = \begin{bmatrix} \int_0^t y(\tau) d\tau \\ y(t) \end{bmatrix} = \begin{bmatrix} x_0(t) \\ x_1(t) \end{bmatrix} \quad (9)$$

$$\begin{cases} dx(t) = Ax(t) + Bu(t) & , x(t) \in R^2 \\ y(t) = C(t) & , y(t) \in R^1 \end{cases} \quad (10)$$

The proposed LQ-PI controller for the interleaved converter is determined by solving the optimal problem to minimize the following cost function, presented as eq. (11) and eq. (12).

$$J(x(t), u(t)) = \frac{1}{2} \int_0^{\infty} (x^T Q x + u^T R u) dt \quad (11)$$

$$u(t) = -Gx(t), G = R^{-1} B^T K \quad (12)$$

where Q and R are the control factor to determine the controller gains. In this paper, we propose the quadratic weighting factor as $Q = N^T N$, and $R = \rho I$, and K is the solution of the Riccati equation shown as eq. (13) [10].

$$KA + A^T K + Q - KBR^{-1}B^T K = 0 \tag{13}$$

The quadratic weighting factors, Q , is factorized as positive semi-definite and symmetric matrix in order to match the controlled state feedback system to frequency domain transfer function by optimal Kalman gain [12].

Because $x(t) \in R^2$ of eq. (10) has two states, control gain matrix G in eq. (12) can be expressed as eq. (14) and optimal control input is determined as the form of eq. (15) with the output and the integral of the output.

$$G = [g_0 \quad g_1] \tag{14}$$

$$u(t) = -\left(g_0 \int_0^t y(\tau) d\tau + g_1 y(t)\right) \tag{15}$$

The control input is represented as a typical PI control state as shown in eq. (16).

$$u(t) = -K_p \left(\frac{1}{K_i} \int_0^t y(\tau) d\tau + y(t)\right) \tag{16}$$

In the design parameter of PI Controller of eq. (16) K_p is a proportional gain and K_i is an integral gain. The relationship between the PI controller and the eq. (14) shows that the control gain matrix is matched to the control gain of LQR as eq. (17) [10].

$$K_p = g_1, \quad K_i = \frac{g_1}{g_0} \tag{17}$$

4. Simulation

In this paper, the numerical simulation is performed by the circuit simulators CASPOC and control design oriented program Matlab/Simulink on the derived mathematical model of three-phase interleaved DC/DC converter in order to show the effectiveness of the proposed control method.

The three-phase interleaved DC/DC converter specifications are shown in Table 1.

Table 1: Parameters for Simulation of the Converter

| Parameter | Value | Unit |
|---------------------|-------|------------|
| DC-Link Voltage | 500 | [V] |
| DC-Link Capacitor | 1 | [μ F] |
| Filter Inductance | 100 | [mH] |
| Switching Frequency | 10 | [kHz] |
| Control Period | 100 | [μ s] |

Figure 3 shows the step response of the three-phase interleaved DC/DC converter controlled by the proposed LQ-PI Controller in time domain. Shown in Figure 3, the internal stability and robustness as infinite gain margin and 60° phase margin are inherently guaranteed by the proposed control method. The circuit diagram of the three-phase interleaved DC/DC converter is shown in Figure 4 for the simulation with CASPOC, in which various power circuit and converters are described by replicating the characteristics of the power systems.

Figure 5 represents the simulation results of the output voltage controlled by the proposed LQ-PI controller, in which the time response shows the good command following and internal stability.

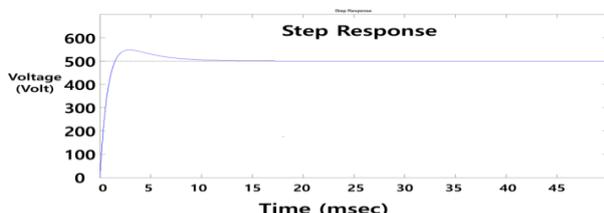


Figure 3: Step Response of Three-phase DC/DC Converter by Matlab/Simulink

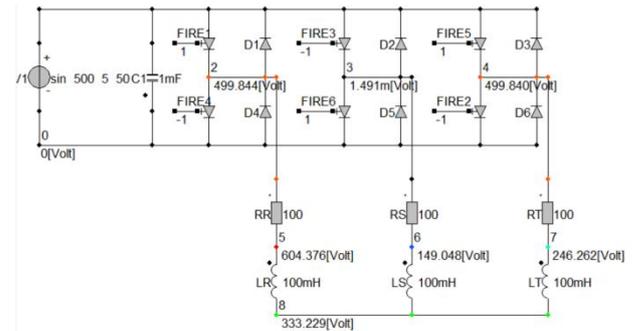


Figure 4: Three-phase Interleaved DC/DC Converter Schematic by CASPOC

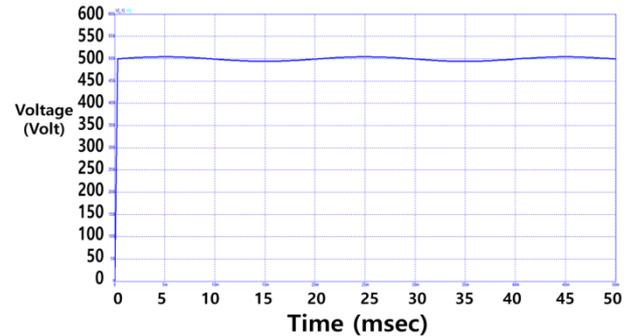


Figure 5: Three-phase Interleaved DC/DC Converter Output Voltage Response by CASPOC

4. Conclusion

In this paper, we proposed the LQ-PI optimal control design method for multi-phase interleaved DC/DC power converter. The controller has the optimal state feedback structure to match the proportional and integral of the system output by a new augmented state.

The proposed control gain is determined to minimize the quadratic performance index for the time- and frequency-domain specifications of the controlled DC/DC converter. Using the proposed control technique, the converter control can be easily tuned and performed without the modulation for switching signals such that output voltage control performance can be considered simultaneously in time and frequency domains. The effectiveness and improvement of the proposed LQ-PI control technique were validated by numerical simulations using CASPOC and Matlab/Simulink.

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