Effective Output Voltage Control of DC-DC Converter under Input Voltage Disturbance for Electric Vehicles

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Abstract—Compared with the conventional vehicular systems, Electric Vehicle (EV) technology is providing an effective solution for achieving higher fuel economy, lower emission, and better performances. In electric vehicular applications, electric storage devices like battery pack or ultra-capacitor module are always required. Efficient charging and discharging of these devices are the main driving force to affect the advantages of electric vehicles (EVs) significantly. Based on the Integrated Powertrain Power Electronic (IPPE) within EVs, the disturbance and variation at DC-link voltage may reduce the efficiency of overall EV system. Especially, in charging mode, this problem not only reduces the charging efficiency but also seriously diminishes the storage lifetime of such devices. In this paper, two simple but effective compensators are designed to control the DC-DC converter. The proposed compensators are able to manage the storage device voltage in a stable manner during charging mode regardless of high variation and disturbance existing on DC-link voltage. In order to validate the effectiveness of the designed compensators, both simulations and experiments are executed.

Keywords: electric vehicle, DC-DC converter, small-signal model, robust control, root-locus method, sisotool.

I. INTRODUCTION

Nowadays, the global warnings such as air pollution, exhausted energy resources, and climate changes have been revealed seriously throughout the world. Especially, in urban area, the pollution coming from the huge exhaust emission of internal combustion engine vehicles are the biggest problem that causes the greenhouse effect. Moreover, due to poor energy conversion efficiency, the conventional vehicles are blamed for the major source of the current energy crisis [1]-[3]. Whereas, the demand of using vehicles in the world is increased dramatically in the past ten-year, and this demand seems to be continued in next decades. So that, to solve such global problems, the conventional vehicle systems have to be replaced by a new generation, which is not only higher fuel economy but also eco-friendly or zero-emission vehicles. New vehicle systems are named as electric vehicles (EVs), cover hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs), and pure electric vehicles (PEVs) [3]-[6].

In electric vehicles, power electronics plays an important role with respect of power conversion unit, traction motor part, battery charger module, and maintenance stage. Because of their efficiency, low-cost architecture, power density, and safety guarantee will be a key in order that the EVs become popular in the market [3]-[4]. To take into account the mentioned specifications, several topologies and techniques are introduced [3]-[9]. Considering of the power conversion unit, one basic but effective topology is shown in Fig. 1. This topology is called the Integrated Powertrain Power Electronic (IPPE), which adopted on Toyota Prius and Camry model [3]. In IPPE, the bi-directional DC-DC converter is used to boost the storage device voltage to a certain DC-link voltage to feed the inverter (boost mode) and feedback the regenerative energy from generator or from utility grid via the on-board charger to the storage devices (buck mode). Normally, to reduce the size and to increase the power density of the power conversion unit, the capacitor at the DC-link should be small in both capacitance and size [4]. However, this will significantly affect the DC-link voltage quality due to high variation and disturbance appearing. Moreover, in charging mode (buck mode), the variation and disturbance also diminish lifetime of the storage devices.

Figure 1. Integrated powertrain power electronic.
In this paper, to deal with such problem, two proper compensators are proposed and designed. Especially, a new equivalent circuit of DC-DC converter basing on the circuit-averaging method is established. This equivalent circuit is useful to derive various transfer functions as well as step responses that provide designer with the converter behavior in detail. Moreover, the linear control theory has been developed firmly so that any problem related to the converter can be solved easily and effectively. With a requirement of removing the effect of the input voltage variation on the output voltage, two transfer functions including the input voltage to the output voltage and the switching duty cycle to the output voltage have been derived first. Subsequently, a suitable control scheme is proposed to analyze for obtaining the proper compensators. Finally, the designed compensators are tested in both simulation and experiment to evaluate their effectiveness.

II. SMALL-SIGNAL MODEL FOR DC-DC BUCK CONVERTER

In buck converter, which is shown in Fig. 2, the switching devices operate as a regulator to regulate the dc output voltage against the load and the input voltage variations with satisfying of transient response standards, steady-state stability requirements, and robustness performances. In addition, the linear control theory has been developed firmly and will offer valuable tools for obtaining good dynamic performances of the converter. However, in order to apply this theory, nonlinear components (switching devices) within buck converter should be averaged and linearized. At this time, there are two methods to handle such requirement, including the state-space averaging method [10], [11] and the circuit-averaging method [12], [13]. The former is based on analytical averaging of state-space equations describing linear equivalent circuits for different states of a converter determined by the on-off status of the transistor(s) and diode(s). However, the state-space averaging method requires considerable matrix algebra manipulation and is sometimes tedious, especially when a converter circuit contains a larger number of elements or parasitic components. Additionally, it provides little insight into the converter behavior. Whereas, the latter leads to linear circuit models by using current- and voltage-dependent sources and the law of energy conservation [13]. The models are relatively simple, provide good intuitive insight into converter behavior, can be used for deriving various transfer functions and step responses. In addition, to apply the linear control theory to regulate the converter against its input voltage disturbance, transfer functions from input voltage to output voltage and from control signal, i.e. switching duty cycle, to output voltage should be established first.

Following the circuit-averaging method, the buck converter is modeled by replacing the nonlinear components by two dependent sources as shown in Fig. 3. This model is named large-signal model, which indicates that every current or voltage component contains a dc signal and an ac signal constituent. In this figure (Fig. 3), \( V_f \) is forward voltage of the diode, \( r_C \) the equivalent series resistance (ESR) of the capacitor, \( D \) is a dc component of the switching duty cycle \( d_f \), \( R_{DS} \) is resistance of the switch, \( r_D \) is the diode resistance, and \( r \) is a total resistance reflected to the output stage

\[
r = D R_{DS} + (1 - D) r_f + r_D.
\]

Based on the circuit-averaging method, all currents, control signal, and voltages in the buck converter, which are \( i_d, i_L, i_o, d_f, v_o \), and \( v_o \) can be considered as sum of a dc component \( (I_d, I_L, I_o, D, V_f, V_o) \) and an ac component \( (i_d, i_L, i_o, d_f, v_o) \) as follows:

\[
i_d = I_d + i_d.
\]

\[
i_L = I_L + i_L.
\]

\[
i_o = I_o + i_o.
\]

\[
d_f = D + d_f.
\]

\[
v_f = V_f + v_f.
\]

\[
v_o = V_o + v_o.
\]

The large-signal model shown in Fig. 3 is nonlinear. Linearization of the model at a given operating point can be obtained by expanding the large-signal nonlinear equation into a Taylor’s series around the operating point, and neglecting the higher-order terms. Subsequently, applying the principle of superposition, the nonlinear model can be considered as two models in separation. The first is a DC signal model shown in Fig. 4 and the second is a small-signal model shown in Fig. 5. Basing on these circuits and using the Kirchhoff’s laws, transfer functions from the input voltage and from the control signal to output voltage are found as follows

\[
G_i = \frac{v_o}{v_i} = K_i \frac{A_i s + A_0}{B_0 s^2 + B_1 s + B_0}.
\]

\[
G_d = \frac{v_o}{d} = K_d \frac{A_i s + A_0}{M_0 s^2 + M_1 s + M_0}.
\]

where: \( A_i = B_0 = N_0 = M_i = 1 \).

\[
K_i = \frac{D R}{R + r} ; \quad K_d = \frac{V_f}{D R + r} ; \quad B_i = M_i = \frac{L(R + r_c)}{R + r}.
\]

\[
A_i = r_i C ; \quad B_i = M_i = \frac{L + r(R + r_c)C + R r_c C}{R + r}.
\]
Looking into the small-signal transfer function of the input voltage to the output voltage $G_{vo}$ given in (8) it is a second-order low-pass filter. Its magnitude form, phase form, and cut-off frequency depend on the converter profile. Fig. 6 shows bode diagram of $G_{vo}$ with the converter profile defined as: $V_i = 155V$, $V_o = 100V$, $L = 1mH$, $C = 470\mu F$, $R = 25\Omega$, $V_F = 1.7V$, $r_{ds} = 0.1\Omega$, $r_s = 0.5\Omega$, $r_c = 0.45\Omega$. The bode diagram indicates that if input voltage of the converter contains low-frequency disturbances (less than 1 kHz), the converter output voltage will be disturbed, which cause high ripples on the output voltage. In EVs, because of the small capacitor in DC-link within the IPPE, the voltage feeds buck converter during charging operation mode will contain high oscillations, whose frequency is even numbers time of the line frequency, i.e., 120Hz, 240Hz, … To solve this issue, the converter has to be controlled by a proper controller.

$$L = CG_{vd}. \quad (14)$$

It is comparable the transfer function $G_{vo}$ with $G_{vd}$, given in (8) and (9), respectively. There is only a difference of their gain $K_1$ and $K_2$. In other words, the bode diagram of $G_{vd}$ is a low-pass filter too and similar to of $G_{vo}$, shown in fig. 6. Moreover, looking at (13), to reject affect of the input voltage disturbances on the output voltage, the open-loop transfer function $L$ should have a high magnitude in low frequency range. So that, there are two simple and popular controllers satisfied such requirement that are a first-order low-pass compensator and a proportional-integral controller.

$$v_o = \frac{G_{vo}}{1+L} v_i. \quad (13)$$
A. Design of the first-order low-pass compensator
A first-order low-pass compensator is defined as:

$$C = \frac{K_a}{s + K_b},$$  \hspace{1cm} (15)

where: $K_a$ and $K_b$ are constants, deciding gain and cut-off frequency of the compensator. It means that, in order to increase the open-loop gain in low frequency range, $K_b$ should be a high constant. However, this will push the open-loop cut-off frequency to the left, leading to worse transient response of the system and worse output voltage performance in steady state if the input contains relative high frequency disturbances or noise from the feedback voltage sensor. To combat this problem, $K_b$ should be increased too. Nevertheless, these increasing may cause closed-loop system become unstable.

To handle successfully the above constraints, a useful and well-known design tool called “sisotool” in Matlab program is selected. The design requirements are set as: the setting time is less than 25ms, the damping ratio is larger than 0.71, and the overshoot is less than 10%. Regulating $K_a$ and $K_b$ to obtain a suitable open-loop transfer function that satisfies the design requirements, its magnitude in low frequency range is as high as possible, the closed-loop system have to be stable, and the cut-off frequency should be larger than 1kHz. Consequently, the compensator is found as follows:

$$C = \frac{156400}{s + 5500}.$$  \hspace{1cm} (16)

In fig. 9, bode diagram of the open-loop transfer function $L$ after adding the designed compensator is plotted. In low frequency range, the magnitude is kept constantly at 36dB. It is large enough to compensate effectively the input voltage disturbance.

![Figure 9. Bode diagram of the open-loop transfer function $L$ after adding a first-order low-pass compensator.](image)

B. Design of the proportional-integral controller
A proportional-integral is defined as followed equation

$$C = \frac{K_p}{s}. \hspace{1cm} (17)$$

where: $K_p$ and $K_i$ are a proportional constant and an integral constant, respectively.

Proportional-integral (PI) controller is a part of proportional-integral-derivative (PID) controller, which is the most popular controller in most of industrial applications because it not only is very simple in designing but also show good performances, including small setting-time, small over-shoot, high damping-ratio, and small error in steady state. As mentioned, the desired compensator should be a low-pass filter that has high magnitude in low frequency range and low magnitude in the other. It seems to be that a PI controller is capable of taking this requirement. Thank to its infinity magnitude at zero-frequency and its integral part, PI controller helps the system remove almost the low frequency disturbances in the output voltage. However, in upper of the cut-off frequency (i.e. $K_i / K_p$), magnitude of the controller is kept at a constant ($20\log K_i$), which make the open-loop system has higher magnitude in high frequency range compared with using a first-order low-pass compensator. This may push the system in worse performances, especially in high noises condition. Therefore, $K_p$ should be designed as small as possible. In contrast, this will affect to the open-loop cut-off frequency, setting-time, or may cause the overall system become unstable. Consequently, obtaining a suitable set of $K_p$ and $K_i$ is a constrain process between robustness requirements such as stability, removing disturbances and noises, or system performances in transient and steady state. In this part, the “sisotool” tool is also used to achieve the proper $K_p$ and $K_i$. The proper controller is found as:

$$C = \frac{4.6s + 20635}{s}.$$  \hspace{1cm} (18)

![Figure 10. Bode diagram of the open-loop transfer function $L$ after adding a PI controller.](image)
In Fig. 10, bode diagram of the open-loop transfer function \( L \) after adding the designed PI controller is shown. The magnitude is higher than 40dB in low frequency range will be able to compensate successfully the input voltage disturbance.

IV. SIMULATION AND EXPERIMENTAL RESULTS

In order to demonstrate the impact of the input voltage disturbance and verify the feasibility of the designed controllers, some simulations and experiments are carried out with the following parameters:

1. AC power supply for the rectifier: \( V_{dc} = 125V / 60Hz \)
2. The output filter capacitors: \( C_f = C = 470\mu F \)
3. The inductor: \( L = 1mH; \ r_L = 0.5\Omega \)
4. The diode profile: \( V_f = 1.7V; \ r_d = 0.07\Omega \)
5. The transistor profile: \( r_{tso} = 0.1\Omega \)
6. The Load: \( R = 25\Omega \)
7. The switching frequency: \( f = 40kHz \)

Both of the designed controllers are executed by a 32-bit, high performance digital signal processor (TMS320F28335) board and a LEM LV-25P voltage sensor is used to measure the output voltage. In addition, a high speed IGBT IRG4PF50W and an ultrafast recovery diode RURG8060 are employed as the switches of buck converter.

![Figure 11](image1.png)

Figure 11. Simulated results for the input voltage \( V_i \) and the output voltage \( V_o \) without any controller.

![Figure 12](image2.png)

Figure 12. Simulated results for the input voltage \( V_i \) and the output voltage \( V_o \) performance by using the first-order low-pass controller.

![Figure 13](image3.png)

Figure 13. Simulated results for the input voltage \( V_i \) and the output voltage \( V_o \) performance by using the PI controller.

In first case, the converter is operated without any controller, the impact of input voltage disturbance on output voltage is proved obviously by a simulation result, shown in Fig. 11. The upper signal is the input voltage waveform \( V_i \) varied from 150V to 180V so that the output voltage \( V_o \) (the lower signal) is disturbed seriously from the input variation. In next case, the converter performs under the first-order low-pass compensator and the PI controller, shown in Fig. 12 and Fig. 13, respectively. The output voltage regulated under both controllers follows the reference voltage \( V_{ref} \) very well although the input voltage contains high variation. However, due to the integration component, performance of the PI controller seems to be lower dynamic response compared with the first-order low-pass compensator.

Next, the experimental results verify feasibility of the proposed controllers in real system. In Fig. 14 and Fig. 15, the output voltage is kept stably at 100V regardless the input voltage varies from 130V to 170V. In Fig. 16 and Fig. 17, dynamic behavior of the proposed controllers is shown by changing the reference voltage between 80V and 100V and the output voltage follows firmly these reference values so that both controllers show high dynamic responses. As similar to the simulation results, the dynamic response of the first-order low-pass compensator is quite faster than that of the PI controller.

![Figure 14](image4.png)

Figure 14. Experimental results: the output voltage \( V_o \) kept firmly at 100(V) by using the first-order low-pass compensator.
V. CONCLUSIONS

In this paper, to obtain a firm output voltage under high input voltage disturbance, two simple but very effective voltage controllers are designed. Those are a first-order low-pass compensator and a PI controller. Both of them verified successfully by both simulation studies and experimental results. Therefore, they can be applied to EVs for achieving a desired output voltage in high performance during charging operation mode for the storage devices regardless of significant voltage disturbance living on the DC-link.

In order to design these effective controllers based on the firmly developed linear control theory, the dynamic transfer functions from input voltage to output voltage and from control signal to output voltage in small-signal characteristic of buck converter are derived. These transfer functions are very useful to introduce some new controllers, whose magnitude should be very high in low frequency range and very low in the rest of one, making the system robust and removing harmful impact of the disturbances and noises as well as achieving fast dynamic response performance.

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