Modeling and Simulation of a Two Cell Automotive Interleaved Buck Converter

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Abstract—This paper focuses on modeling and simulation of a 42V/14V dc/dc converter based architecture. This architecture is considered to be technically a viable solution for automotive dual-voltage power system for passenger car in the near future. An interleaved dc/dc converter system is chosen for the automotive converter topology due to its advantages regarding filter reduction, dynamic response, and power management. Presented herein, is a model based on one kilowatt interleaved two-phase buck converter designed to operate in a Continuous Conduction Mode (CCM). The control strategy of the converter is based on a voltage-mode-controlled Pulse Width Modulation (PWM) with a Proportional-Integral-Derivative (PID). The effectiveness of the interleaved step-down converter is verified through simulation results using control-oriented simulator, MatLab/Simulink.

Index Terms—Automotive, dc-to-dc power modules, design, interleaved, MatLab/Simulink and PID control.

1. INTRODUCTION

A switching converter is an electronic power system which transforms an input voltage level into another for a given load by switching action of semiconductor devices. A high power efficient dc/dc converter is strongly desired and has found widespread applications. Examples include aerospace [1], sea and undersea vehicles [2], electric vehicles (EV), Hybrid Electric Vehicle (HEV) [3], portable electronic devices like pagers [4], and microprocessor voltage regulation [5].

In dual-voltage vehicular electrical systems, the dc-to-dc converter is required to step-down the high-voltage to provide back up compatibility for the existing low-power devices such as incandescent lamps, small electric motors, control units and key-off load (clock, security system). A schematic of the 42V/14V dc-to-dc converter architecture is shown in Fig.1, with the possibility of either single or a dual battery (12V and 36V). The aim of the 42V/14V architecture of Fig.1 is to reduce the cost, weight and packaging space created by the additional 12V energy storage battery. Ideally, the power management system should be smart enough to manage the key-off loads from depleting the high voltage battery to the point that the car cannot be started [6, 7, 8, 9]. The philosophy behind dual battery system architecture is that the starting function should be isolated from the storage function required for the key-off loads [8, 9].

Fig.1 The 42V/14V system architecture

For automotive application where volume, weight, and cost are particularly important, the preferred choice is the single battery 42V/14V system architecture with centralized system structure. Furthermore, the removal of the 12V battery does not alter the dynamics of operation of the power converter. However, the power from the converter must cover the power requirement of all the 14V power loads (approximately1kW) under the worst-case scenario. In addition, the non-isolated dc/dc converter topology is the most appropriate architecture because isolation between 42V and 14V buses is not required in automotive power net and has the advantage over the transformer-isolation types in terms of the easy-to-design circuit configuration, low volume, weight and cost.

An important portion of the integrated circuit industries such as (Linear Technology Corporation and Texas Instrument) are focusing their efforts in developing more efficient and reliable step-down (Buck) converters. In academia, research studies into analysis, modeling and simulation of 42V/14V dc/dc converters have made progress in various disciplines, including thermal, electrical and mechanical analysis. A strategic methodology to the design power electronic equipments is presented in [9]. Investigation of computer-aided design (CAD) tool to calculate the number of phases to optimize cost, size, and weight is offered in [10]. The power losses in a 500W converter as a function of the number of phases are explained in [11]. The effect of number
of cells on the passive component using software tool called PExprt is carried out in [12]. A comparison between multi-phase converters with a conventional single-switch buck converter is carried out in [5]. State of the art engineering for multi-phase dc/dc converter may range from three, four to five paralleled buck stages [10] or even as many as 16 and 32 phases [13].

In this paper, a model based on one kilowatt interleaved two-phase dc-to-dc buck converter designed to operate in a Continuous Conduction Mode (CCM) controlled by voltage-mode-controlled Pulse Width Modulation (PWM) with a Proportional Integral Derivative (PID) is presented. The effectiveness of the interleaved step-down converter system is verified through simulation using control-oriented simulators, MatLab/Simulink.

II. MULTIPHASE SWITCHING OF DC-TO-DC CONVERTERS

To realize power conversion by a simple system configuration, a multi-cells buck converter topology designed for CCM of operation is employed. Fig.2 shows the developed Simulink diagram of a two-cell interleaved buck converter with PID Controller. The two-cell interleaved buck converter is connected in parallel to a common output capacitor and sharing a common load with associated control system. The low-voltage side is connected to the 14V automotive electrical loads while the high-voltage side to the on-board power generator (alternator) with nominal input voltage of 42V, and range between 30V and 50V during normal operation.

In this interleaved two-cell dc/dc converter architecture, the cells are switched with the same duty ratio, but with a relative phase shift or time interleaved introduced between the two cell in order to reduce the magnitude of the output ripple at the output port of the converter. The overall output current is achieved by the summation of the output currents of the two cells and found to be continuous.

The ripple reduction helps to reduce the filtration requirements needed to contain any EMI the converter produces and thereby decrease the constraints on the electronic components connected to the low-voltage bus. Furthermore, due to the equal sharing of the load current between the two cells, the stress on the semiconductor switches is reduced and thereby reliability is improved. Another advantage is the ability to operate the converter when a failure occurs in one cell as well as the possibility to add new cells to the converter with minimum effort.

To design this converter, the following automotive specifications for dual-voltage automotive electrical systems [9, 10] must be fulfilled and are tabulated in table 1. The specifications of the converter should meet the demand of the 14V electrical loads of 71A, operating temperature range -40°C to 90°C and the tight EMI requirements to prevent the converter from interfering with other equipment in the car.

III. COMPONENT SELECTION

For low voltage/high current power converter, the usage of MOSFETs switching devices with low on-resistance is required for more efficient and practical power conversion. The inductors and capacitors play important roles in the design of the power converter. Inductor is an energy storage element while the capacitor is the main buffer for absorbing the ripple current generated by the switching action of the power stage. The switching frequency of the power electronics used in automotive industry ranges from 82 kHz to 200 kHz with 100 kHz as a typical value used for most operation of dc/dc converters.

Based on the switching frequency, input/output voltages and the duty ratio, the inductance value to guarantee that the converter cells would run in the continuous conduction mode over the entire operating range can be calculated using (1) [14]

\[
L_{\text{critical}} = \frac{V_i D^2}{2 f_s I_{\text{max}}} \times \frac{V_i - V_o}{V_o}
\]
Where: \[ L \text{critical} \] is the converter switching frequency, \( D \) is switching duty cycle for the MOSFET and \( \text{Vi and Vo} \) are the input and output voltages respectively.

Since this is a two-phase interleaved converter, the power stage inductance of each phase is therefore equal to 15\( \mu \)H. The output capacitor is another important element, which may reduce the system cost in multi-phase converter system and is needed to keep the output voltage ripple \( \Delta V_o \) within allowable output voltage range.

To meet these constraints of the design specifications, the capacitor value does not necessarily need to be very large to smooth the output voltage. Fig 3 shows the capacitor variation from 100\( \mu \)F to 400\( \mu \)F along with the value of voltage ripple. To meet the constraint of the design requirements concerning the voltage ripple of the converter system, a capacitor value of 300\( \mu \)F is sufficient.

**IV. SIMULATIONS RESULTS**

The ability to model and simulate engineering design of a complete power electronic converter system is essential before proceeding to the engineering experimental phase. Hence, simulations are important for design validations and cost-effectiveness as the power-conversion product development.

The complete model of the Simulink implementation of the internal structure of the interleaved two-phase buck converter system of Fig.2 is divided into three main parts; the two-cell buck converter, the voltage-mode-controlled PWM with a PID controller and the phase shift interleaving circuit. The multi-phase converter has been simulated to obtain the necessary waveforms that describe the converter system operation under steady-state and transient conditions, using the design parameters tabulated in table 2.

**TABLE 2**

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>( \text{Vi} )</td>
<td>42</td>
<td>V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>( \text{Vo} )</td>
<td>14</td>
<td>V</td>
</tr>
<tr>
<td>Number of phases</td>
<td>( N )</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Inductor value</td>
<td>( L )</td>
<td>15</td>
<td>( \mu )H</td>
</tr>
<tr>
<td>Capacitor value</td>
<td>( C )</td>
<td>300</td>
<td>( \mu )F</td>
</tr>
<tr>
<td>Load resistance</td>
<td>( RL )</td>
<td>0.196</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>( fs )</td>
<td>100</td>
<td>kHz</td>
</tr>
</tbody>
</table>

**A. Ripple Cancellation**

The first step in the analysis of the multi-phase interleaved converter system is to investigate the effectiveness of ripple-cancellation. It can be seen from Fig. 4 that the ripple of the output voltage and the total inductor current of the power converter system are better than the desired specified limits indicated in table 1. From the results it can be observed that the converter achieved a very good current and voltage ripple cancellation.

The results also show that the EMI filter is not needed to reduce the peak to peak voltage ripple on the 14V terminal. This may lead to the elimination or redesign of the protection circuitry connected to the 14V bus.

Fig 4 shows the steady-state waveforms of the individual cell currents, the total output inductor current and the output voltage. The simulated results show that the curves of the two individual cell currents are balanced and the time interleaved of the cells is apparent from the relative time delay of each cell's inductor current. The inductor current in each cell rises from 3.25A to 3.9A during each switching period and goes through an interval in the continuous conduction mode.

The sum of the individual cell currents result in a total current of 7.14 A with a ripple current of around 4mA which is less than the individual cell ripple current.

The simulated results indicate that, the operation of the power converter system is stable and accurate. The converter is able to respond and produce the desired stable output voltage and deliver the required total output current to the load with very low ripple. As a result, no negative effect on the connected loads, such as small motors, lights and accessories.
The interleaved dc/dc buck converters are used as power source to resistive and dynamic loads (small and very small motors) in passenger car. The electrical load demand varies and depends upon the weather and the driving conditions. A full load condition is rarely present for a prolonged period of time and most of the devices run at light loads (stand-by-mode) for most of the time.

To study the effect of the load variation on the dynamic behavior of the converter system, the load at the output of the converter system is suddenly changed from 50% to 75% and than back from 100% to 75% and 50% of the full load at time t=0.002, 0.004 and 0.006s respectively. The simulated results are shown in Fig.6.

It can be seen that for the output voltage the initial overshoot is about 21V which makes a variation of 7V, however, there is very minimal change when the load at the output of the converter system was suddenly changed from 50% to 75% and to full-load (1kW).

The results show that the performance of the system is stable and well behaved under load variations (disturbances) and the output voltage remains within the desired specified limits presented in table 1, apart from the initial transient.

C. Input Voltage Variation

In real conditions, the alternator output voltage ranges from 30V to 50V during normal operation, with nominal voltage of 42V. To study this line of variation, a step change in the input voltage from 33V to 50V is applied to the model. Fig.7 shows a transient response of the output voltage behaviour waveform due to sudden changes in the input voltage of the power converter system.

At the beginning of the cycle, at time t=0.002s, the input voltage suddenly rises from nominal system voltage of 42V to 50V. The maximum output voltage (bottom trace) transient overshoot is about 21V which makes a variation of 7 V, however, there is very minimal change when the load at the output of the converter system was suddenly changed from 50% to 75% and than back from 100% to 75% and 50% of the full load at time t=0.002, 0.004 and 0.006s respectively. The simulated results are shown in Fig.6.

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D. Load and Supply Voltage Variations

The combinations of both the supply-voltage and load variations that occur in the converter system have been simulated and the outputs are presented in Fig.8. It can be observed that the designed system has a low-sensitivity to the load and supply-voltage variations. These variations have only small influence on the output voltage and load current and still respect the specifications of the automotive standard. It can be concluded that from the results obtained the proposed converter can maintain the desired output voltage independently of load and supply-voltage variations. This may lead to the elimination or redesign of protection circuitry for electronics connected to the 14V bus.

...application to a Voltage Regulator Module (VRM) is straightforward and it can be easily extended to cover other topologies. The characteristic of the interleaved two-phase dc-to-dc buck converters system was verified using circuit simulation.

It can be concluded that the initial transient behaviour of a two-cell buck converter introduces a higher inrush currents and voltages compared to a six cell counterpart. Moreover, it introduces more harmonics into the system. On the other hand this topology, is simple to implement, reduced size and cost.

REFERENCES


CONCLUSIONS

Analysis, design and simulation of 42V/14V interleaved two-phase dc-to-dc buck converters system with one kilowatt output power have been presented. This system is aimed for the next-generation cars which will have a 42V/14V dual-voltage electric power system.

Based on the simulation results, the performance of the dc-to-dc buck converter system provides a number of features that do not exist in today’s automotive electrical power systems. Among these features is the low ripple-current in each phase, which leads to reducing switching losses, and a fast transient response as well as a well-regulated 14V bus even in the absence of a 12V storage battery. Therefore, no transient suppression is necessary at the 14V output.

This improved transient response may lead to the elimination or redesign of protection circuitry for electronics connected to the 14V bus. Moreover, good stability, robustness, fast dynamic response and equal current distribution were achieved; at the same time the specification of the automotive standards were respected. Nevertheless, its