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Design of a DC-DC Regulator for Hybrid Electric Vehicles based on a Quadratic Step-Down Converter

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Abstract— **In this work, a switching regulator is developed based on a quadratic-based step-down converter combined with an input filter that provides a wide conversion ratio of output voltage and non-pulsating input current; thus, it is suitable as an interface between lithium-ion batteries and on-board applications of hybrid electric vehicles. Simple and easy-to-use expressions for the proper selection of the converter and the robust controller parameters are obtained, and a brief discussion about the LC filter added to the input port may cause closed-loop instability. Test results in a laboratory prototype with an output power of 300 W show the time and frequency responses.**

I. INTRODUCTION

Due to the growing need for greenhouse gas reduction, particularly CO_2 emissions, the automotive industry is proposing a more efficient use of energy and low-carbon energy, including manufacturing of hybrid electric vehicles. One proposed scheme [1] is the 48V system shown in Figure 1, which includes an electrical machine, a 48 V Lithium-ion battery, and a 48/12V DC/DC converter. The converter is used to power on-board equipment, like sensors for current, positions, and temperature, as well as heaters and electric pumps, which are typically powered by 12V.

Lithium-ion batteries (LIB) are preferred in hybrid electric vehicles because lithium is a very reactive element [2] with a high energy density; therefore, smaller sizes and weights are preferable to other rechargeable batteries with similar power characteristics. A drawback is the variations of its output voltage that depend on the battery charge, and another is related to high ripple currents or high harmonics currents that are detrimental to a LIB life span.

II. STEADY-STATE ANALYSIS OF PROPOSED CONVERTER

The switching regulator developed is based on non-cascaded quadratic step-down converter combined with an input filter (QCIF), shown in Figure 2, which provide a high conversion ratio of output voltage and prevents the strong electromagnetic interference (EMI) due to pulsating input current and the switching action of the semiconductor devices.

The expressions for the relationship of converter variables in steady-state conditions are:

$$V_{Cin} = V_{in},\ V_{CT} = V_{in}D(1-D),\ V_O = V_{in}D^2 \qquad (1)$$

$$I_{Lin} = V_{in}D^4 / R,\ I_{L1} = V_{in}D^3 / R,\ I_{L2} = V_{in}D^2 / R \qquad (2)$$

and assuming negligible voltage drops on the switching devices, the voltage and current ripples, that allow to carry out the value of the electric elements of converter are:

$$\Delta I_{L_{in}} = (V_{in} - v_{C_{in}}) / L_{in} f_S \qquad (3)$$

$$\Delta I_{L_1} = [V_{in}(1-D)D] / L_1 f_S \qquad (4)$$

$$\Delta I_{L_2} = [V_{in}(1-D)D^2] / L_2 f_S \qquad (5)$$

$$\Delta V_{C_T} = [V_{in}(1-D)D^3] / C_T R f_S \qquad (6)$$

$$\Delta V_{C_O} = [V_{in}(1-D)D^3] / C_O R f_S \qquad (7)$$

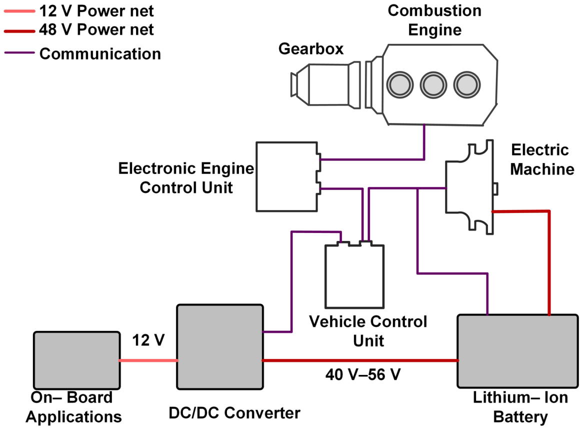


Figure 1. Hybrid 48 V/12 V system.

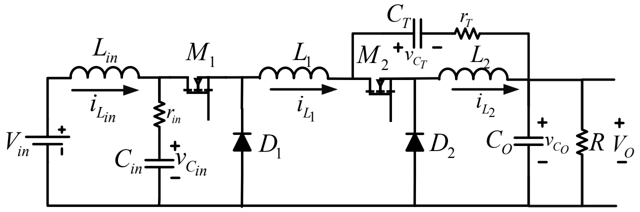


Figure 2. Non-cascaded quadratic step-down converter combined with an input filter,

II. DYNAMICAL ANALYSIS OF CONVERTER

For the proposed topology, state-space equations without and with considering the effect of ESR of inductors and capacitors were obtained, as well as low-frequency continuous nonlinear model. By using linearization techniques around the operating point in this nonlinear model, a linear model was carried out.

Based on the resulting linear model, the Laplace transforms are applied to analyze the dynamic behavior of the converter. This analysis mainly focuses on the transfer function output voltage-to-duty cycle to determine the effect that the electric elements and ESR of the input filter capacitor have on the dynamic behavior of the QCIF and its output voltage. The resulting transfer function has the form:

$$\frac{v_O(s)}{d(s)}=\frac{-b_5s^5+b_4s^4-b_3s^3+b_2s^2-b_1s+b_0}{s^6+a_5s^5+a_4s^4+a_3s^3+a_2s^2+a_1s+a_0} \quad (8)$$

where a_i and b_i with i = 0...5 are the denominator and numerator polynomial coefficients. The expressions for the coefficients are too large, so they are obtained by numerical results based on the values of the converter.

It is found that the converter is stable and has non-minimum phase behavior; however, if the ESR of the capacitor input filter is added to the model, some of the b_i coefficients become positive, which reduces the number of zeros on the right-hand side (RHS) of the s-plane. Furthermore, in physical applications, this characteristic can exhibit different values depending on the dielectric used in the capacitor by the manufacturer.

III. CONTROLLER DESIGN FOR THE CONVERTER

The controller must efficiently mitigate the voltage changes in the output produced by the operational conditions, for example, changes in input source voltage and output load. When lithium-ion batteries are used, they exhibit voltage variations up to 15% of their nominal value.

The block diagram for the control scheme is shown in Figure 3, where V_{ramp} is a ramp waveform, which is compared with the control signal. A low-pass filter F(s) has a high-frequency pole, a high-gain compensator G(s) is added in the internal current loop, v_{ref} is the desired voltage, N and H are the current and voltage sensor gains, and PI is the controller of the external voltage loop.

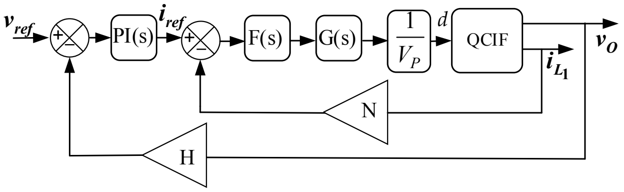


Figure 3. Control scheme block diagram.

The control system design criteria are based on the loop-shaping technique. The following conditions should be satisfied for good performance of the switching regulator:

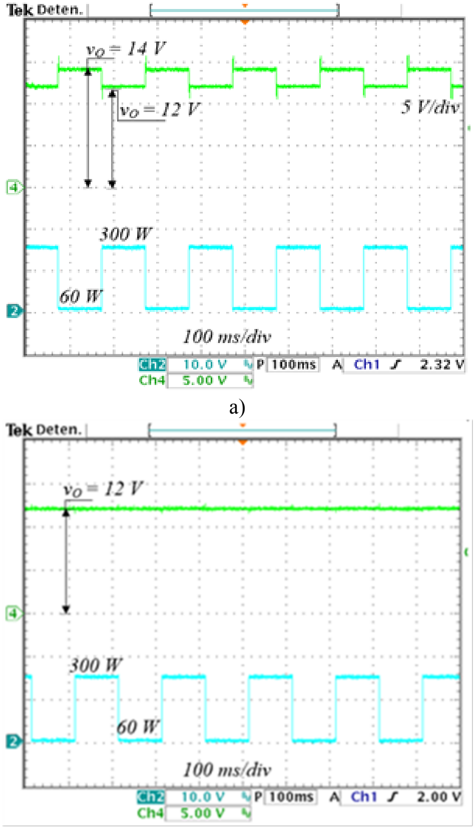
a) For voltage regulation, the voltage loop gain should be high at low frequencies and low at high frequencies

b) For robustness, good gain and phase margins are required.

The above conditions should be satisfied with the two control loops of the current-mode control; however, the PI-controller of the outer voltage loop plays an important role. The pole of PI-controller helps with voltage regulation and robustness. In general, gain margins of 2–10 dB and phase margins of 30–60 degrees are desirable tradeoffs between bandwidth and stability in the closed-loop system.

IV. EXPERIMENTAL RESULTS

The proposed converter and regulator were built in the laboratory to validate the theoretical development with the nominal conditions for the on-board converter in a hybrid electric vehicle: an input voltage of 48V, an output voltage of 12 V, and an output power of 300 W.



a)

b)

Figure 4. Experimental response of output voltage waveforms with load changes in the prototype: a) controller disable, b) Controller enable.

V. CONCLUSIONS

Lithium-ion batteries with an output voltage of 48V or more are preferred in hybrid electric vehicles to supply the required electric power. A DC-DC converter regulated by a control scheme is necessary to feed this voltage to on-board equipment powered by 12 V.

References

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[2] Brand, M. J.; Hofmann, M. H.; Schuster, S. S. The influence of current ripples on the lifetime of lithium-ion batteries. *IEEE Trans. Veh. Technol.*, 2018, 67, 10438-10455. https://doi.org/10.1109/TVT.2018.2869982.