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Interleaved Double Dual Boost Converter for Renewable Energy System

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Keywords: Interleaved converter; Flatness system; Sliding-mode control.

Abstract. This paper presents an interleaved double dual boost converter (IDDB) used in renewable energy application where high voltage gain is required such as fuel cell or photovoltaic applications, etc. Two types of controllers are applied to this converter, 1) a controller based on Flatness properties for regulating the output voltage (outer loop); 2) a sliding mode controller for inductor current (inner loop). The variation of the input voltage is compensated by trajectory planning process. The validation of the proposed system is done through experimental results.

Introduction

According to the exponentially increasing of electricity demand in industrials, transportation and residential sectors and also with the climate changing problem, human urgently needs an alternative method to generate electricity. The next generation of electricity production should be inexpensive and friendly with environmental. This is why the advent of renewable energy is very important. The most attracted renewable energy sources are solar energy, hydrogen energy, and wind energy. Most of the electricity generated from the renewable energy sources is direct current with relatively low level of potential. There are many standard of electricity specifications have found in literatures e.g. AC 110 V 60 Hz, AC 220 V 50 Hz or DC 42 V, DC 270 V, DC 540 V. Although the DC can be converted to AC by an inverter, the DC voltage at the input of the inverter must greater than the AC output voltage. The boost converter is commonly used to convert the relatively low DC voltage obtained from the renewable energy sources to a higher level for fulfilling the requirement of the inverter. Unfortunately, losses in the converter limit the voltage gain to under a certain value. We can find the voltage gain about 3-4 times in literatures. In [2], authors have proposed a converter using two conventional boost converters but connected in a special way. This converter gives two advantages: 1) the output voltage gain is high compared with the conventional one and 2) the input current ripple is low due to using interleaving technique.

In this paper, an interleaved double dual boost converter is study for DC renewable energy applications. To control this converter, we propose to use a nonlinear control, which is based on Flatness system properties [3,4] to control the energy, which is an image of the output voltage, stored in the output capacitor. Whereas the sliding-mode control technique [5,6] is applied for the current loop.

Interleaved Double Dual Boost Converter

The schematic diagram of the interleaved double dual boost converter is shown in Fig. 1. For the sake of simplicity, all losses are neglected except specified and the input voltage is constant. This converter consists of two conventional boost converters each called a sub-converter. The first one is connected to input voltage source as usual, but the second one is slightly different. Nonetheless, both converters are identical and when they work under continuous conduction mode (CCM), the voltage gain can be described as:

$$\frac{V_{2,1}}{V_1} = \frac{V_{2,2}}{V_1} = \frac{1}{1-\alpha} \tag{1}$$

where α represents the duty cycle.

For the whole converter, the output voltage V_2 depends on the two output voltages ($V_{2,1}$ and $V_{2,2}$) of each sub-converter and the input voltage V_1 as shown in (2). With the assumptions we made, the output voltage can be controlled by controlling the output capacitor voltages $V_{2,1}$ and $V_{2,2}$ whereas the input voltage V_1 is constant.

$$V_2 = V_{2,1} + V_{2,2} - V_1 \tag{2}$$

The input current i_1 is the difference between the sum of the current of each sub-converter and load current:

$$i_1 = i_{11} + i_{12} - i_2 \tag{3}$$

The switches of the two sub-converters can operate in the same on-off timing or can operate in interleaving manner. For the interleaving operation, both switches conduct at the same switching frequency with the phase shifting from one to another by $T/2$ as shown in Fig. 1. With interleaving technique, the input current ripple is reduced. The phase of each converter can be paralleled N-phase like conventional interleaved boost converter to decrease ripple current and increase the input current capability.

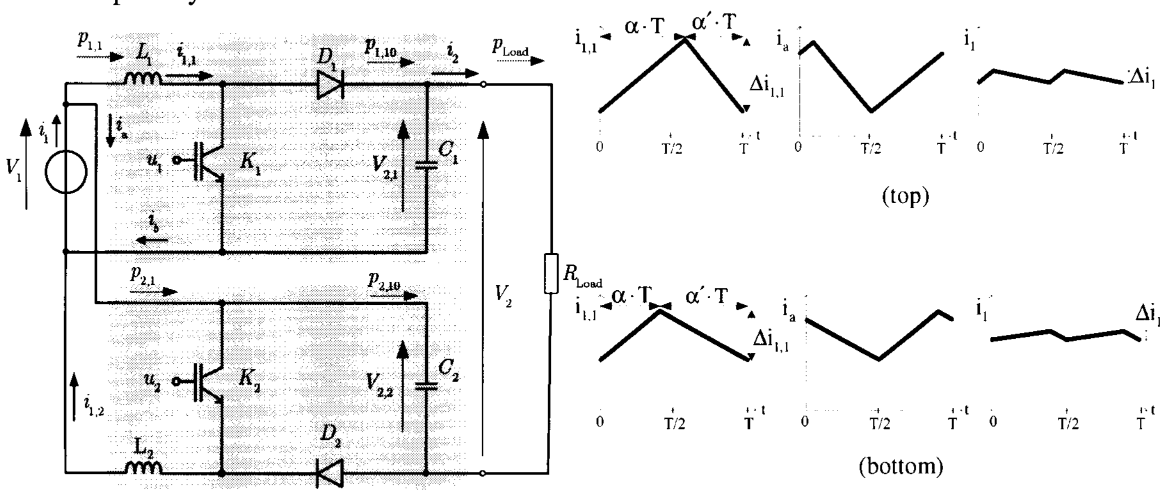

Fig 1. Interleaved double dual boost converter and key waveforms of IDDB, (top) duty cycle α > 0.5, (bottom) α < 0.5.

CONVERTER MODELING AND CONTROLLERS

To control this converter, two control loops are used as detailed in Fig. 2. The energy stored in the output capacitor is controlled as outer loop whereas the inductor current is considered as inner loop.

Outer loop. In 90s, Fliess and his team proposed Flatness system [3]; their contributions have been applied to vast applications not only in mechanical domains but also electrical domains [3]. They have showed that if state variables and control inputs of any system can be found in function of the considered flat outputs and their time derivative(s), that system is the differential flatness system. The outstanding advantage of such system controlled using flatness system properties is that the desired trajectories of the considered flat outputs can be designed both transient and steady states. The energy stored in the output capacitor corresponding to the output voltage, which is a state variable, is chosen as a flat output. It can be expressed in function of Y:

$$Y = [y_1 \;\; y_2]^t = \left[\frac{1}{2}\, C_1 \cdot V_{2,1}^2 \;\; \frac{1}{2}\, C_2 \cdot V_{2,2}^2\right]^t \tag{4}$$

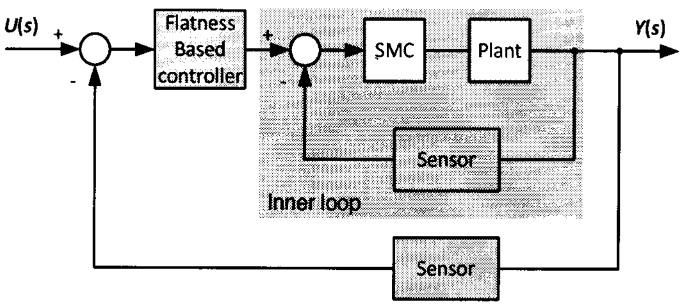

Fig 2. Control block diagram.

The state variable X can be written in function of the chosen flat output:

$$X = [x_1\ \ x_2]^t = \left[\sqrt{\frac{2\cdot y_1}{C_1}}\ \ \sqrt{\frac{2\cdot y_2}{C_2}}\right]^t = [\emptyset_{y1}(y_1)\ \ \emptyset_{y2}(y_2)]^t \quad (5)$$

The dynamic of energy stored in each capacitor depends on the power fed in the capacitor and delivered to load:

$$\dot{y}_1 = P_{1,10} - P_{\text{Load}(+)}$$
$$\dot{y}_2 = P_{1,20} - P_{\text{Load}(-)} \quad (6)$$

$$\Rightarrow \dot{y}_1 = P_{1,1} - r_1\cdot\left(\frac{P_{1,1}}{V_1}\right)^2 - P_{\text{Load}(+)},\ \dot{y}_2 = P_{1,2} - r_2\cdot\left(\frac{P_{1,2}}{V_1}\right)^2 - P_{\text{Load}(-)} \quad (7)$$

By considering the input power of each sub-converter as a command P_{ref} and the input voltage is constant, one can express: $U = [u_1\ \ u_2]^t = [p_{1,1}\ \ p_{1,2}]^t$ (8)
where

$$p_{1,1} = 2\cdot P_{1,1max}\cdot\left(1-\sqrt{\frac{\frac{\left(\sqrt{\frac{2\cdot y_2}{C_2}}+\sqrt{\frac{2\cdot y_1}{C_1}}-V_1\right)^2}{R_{Load}}+\dot{y}_1}{P_{1,1max}}}\right) = \varphi_{u1}(y_1, y_2, \dot{y}_1)$$

$$p_{1,2} = 2\cdot P_{1,2max}\cdot\left(1-\sqrt{\frac{\frac{\left(\sqrt{\frac{2\cdot y_2}{C_2}}+\sqrt{\frac{2\cdot y_1}{C_1}}-V_1\right)^2}{R_{Load}}+\dot{y}_2}{P_{1,2max}}}\right) = \varphi_{u2}(y_1, y_2, \dot{y}_2) \quad (9)$$

Note that, in the control aspect, y_1 and y_2 are reference signals. And it will be generated (trajectory planning) to taken into account of constraints of the system such as the variation of the input voltage, surge current in the output capacitors detailed in Fig. 3. This reference signal is fed to a low-pass second order filter (dynamic limitation block). $P_{1,j\,max} = V_1^2/(4\cdot r)$ represents the maximum power transferred to load of the j[th] sub-converter corresponding to the series resistance r. To ensure that the flat output vector will equal its reference, the following control law expressed is used. The modeling error will be compensated by the integral term:

$$V = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_1 - \dot{y}_{1\text{REF}} + 2\cdot\zeta\cdot\omega_{n1}\cdot(y_1 - y_{1\text{REF}}) + \omega_{n1}{}^2\cdot(y_1 - y_{1\text{REF}}) \\ \dot{y}_2 - \dot{y}_{2\text{REF}} + 2\cdot\zeta\cdot\omega_{n2}\cdot(y_2 - y_{2\text{REF}}) + \omega_{n2}{}^2\cdot(y_2 - y_{2\text{REF}}) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

where ζ and ω_{n1} and ω_{n2} are damping factor and angular frequency of the closed loop system. ω_{n1} and ω_{n2} are selected to be lower than that of the closed loop of the inner loop.

Inner loop. The inductor current in each sub-converter is controlled separately. Their references are generated from the outer loop controller. The controller can be either linear or nonlinear controller. It is well-known that choosing of parameters of linear controller is based on linearized model and the closed loop dynamic of the system will depend on the operating point. This limitation does not occur in the case of using nonlinear controller. The average current models of the converter are

$$\frac{d}{dt}i_{1,1} = \frac{1}{L_1}\cdot(V_1 - r_1\cdot i_{1,1} - (1-u_1)\cdot V_{2,1}),\ \frac{d}{dt}i_{1,2} = \frac{1}{L_2}\cdot(V_1 - r_2\cdot i_{1,2} - (1-u_2)\cdot V_{2,2}) \quad (11)$$

where u_1 and u_2 represent the duty cycle values of the control signals of the switches K_1 and K_2.

With the sliding surface defines as (9), and its derivative is:

$$S_j(x) = i_{Lj} - I_{ref} + k\int_0^t (i_{Lj} - I_{ref})\,dt \tag{12}$$

$$\dot{S}_j(x) = \frac{d}{dt} i_{Lj} - \dot{I}_{ref} + k(i_{Lj} - I_{ref}) = -\lambda \cdot S_j(x) \tag{13}$$

where λ is speed attraction coefficient of the sliding-mode control [6].
By replacing (7) into (10), the commands for the j^{th} converter can be obtained:

$$u_j = -L_j \cdot \frac{\lambda}{V_2} \cdot S_j(x) + r_j \cdot \frac{i_{1,j}}{V_2} - \frac{V_1}{V_2} + 1 - \frac{L_j . k \cdot (i_{Lj} - I_{ref})}{V_2} + \frac{\dot{I}_{ref}}{V_2} \cdot L_j \tag{14}$$

The coefficient λ and k are chosen to make the closed loop system stable.

EXPERIMENAL RESULTS

The prototype of the proposed converter is based on SEMISTACK module using IGBTs (SKM50GB123D) manufactured by Semikron. The parameter of the converter are following: V_1 = 26 V, V_2 = 80 V, inductors L_1 and L_2 = 0.3 mH, output capacitors $C_1 = C_2$ = 1100 μF, switching frequency f = 10 kHz, ω_n = 100 rad.s^{-1}, ζ = 0.707, λ = 5 and k = 1000, ω_f = 10 rad.s^{-1}, ζ_f = 1. The control algorithms and PWM are realized under Matlab/Simulink with dSPACE 1104 interfacing card. The test bench is depicted in Fig. 4.

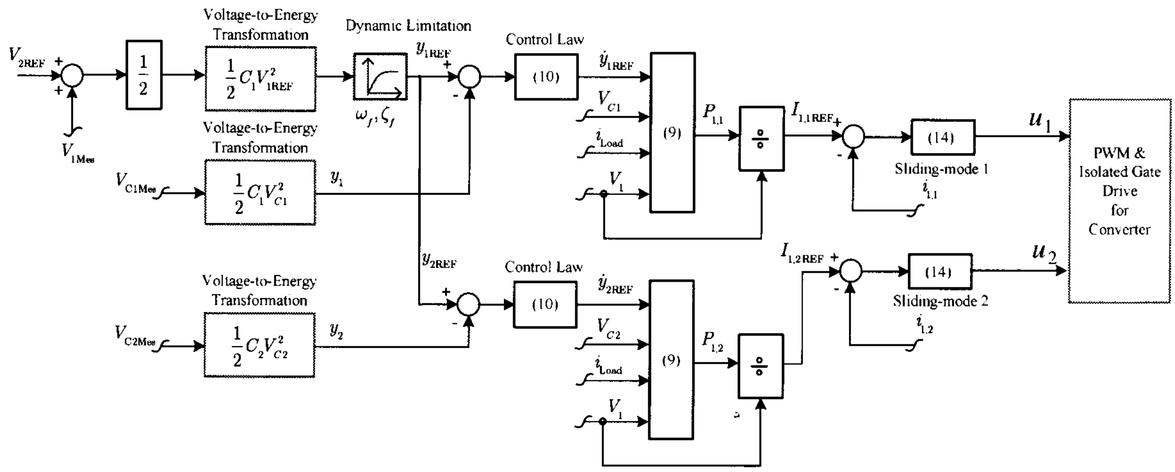

Fig. 3. System Block control of IDDB.

Fig. 5 shows start – up response of the proposed system where the initial output voltage equals to the input voltage V_l = 26 V and load resistance is about 11 Ω. The flat output, which is the energies stored in the output capacitor y_1 and y_2, track well their references $y_{1ref} = y_{2ref}$. Fig. 6 shows tracking property of controlled system when the output voltage V_{2ref} corresponding to the energies $y_{1ref} = y_{2ref}$ was varied from 50 V to 80 V and return 50 V. The response of energies and load current of the converter are depicted in Fig. 7. The resistive load was changed and the output power then varies from 250 W to 500 W and return to 250 W. The energies stored in the capacitors C_1 and C_2 are perturbed from load and then they can return the setting point in finite time. In Fig. 8, the current of each phase and the input current are depicted in steady state. The ripple of the total current is reduced about 80% compared to the current of each phase.

Summary

The paper has presented two-loop nonlinear controllers for an interleaved double dual boost converter using sliding-mode control for the inductor currents and the controller based on Flatness property for the image of the output voltage. One of the advantages of flatness control is that the system behaviors can be known both in the transient and steady state. Moreover, choosing energy stored in the output capacitor as flat output yield an advantage of insensitive to noise. By using interleaving technique, the input ripple current is reduced. The experimental results reveal a good performance and the validity of the proposed control strategy.

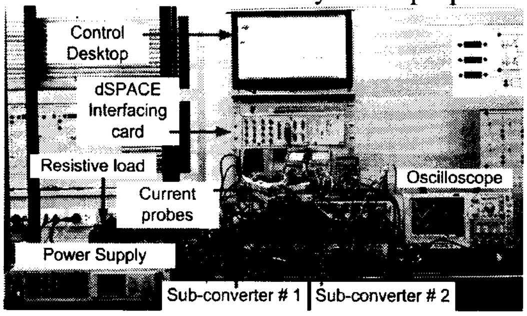

Fig. 4. Test bench.

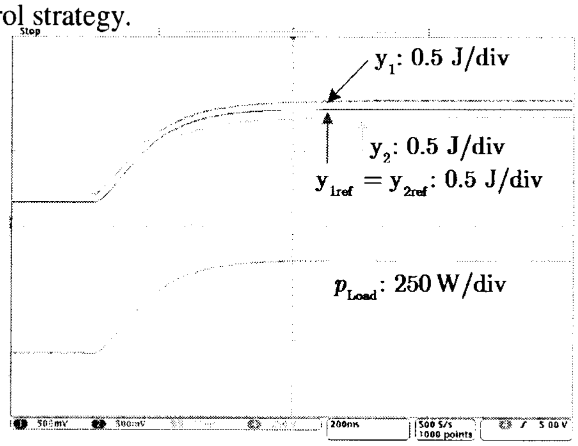

Fig. 5. Start-up response of the proposed system where the initial output voltage is V_1 = 26 V.

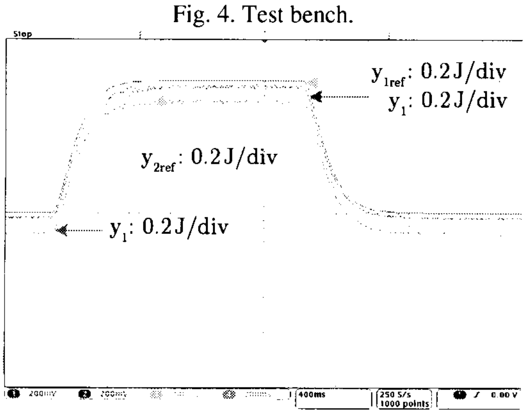

Fig. 6. Response of the energy stored in the output capacitor corresponding to output voltage.

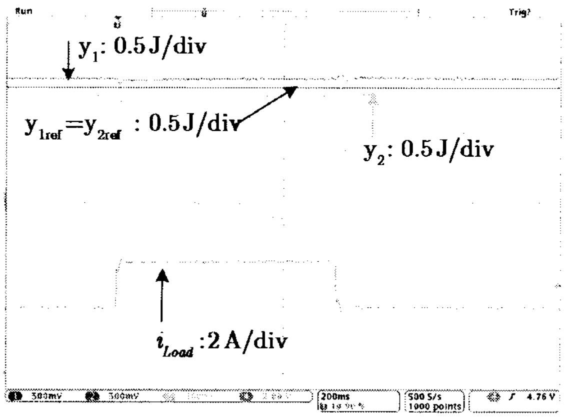

Fig. 7. Response of system for a load step from 250 W to 500 W and return to 250 W.

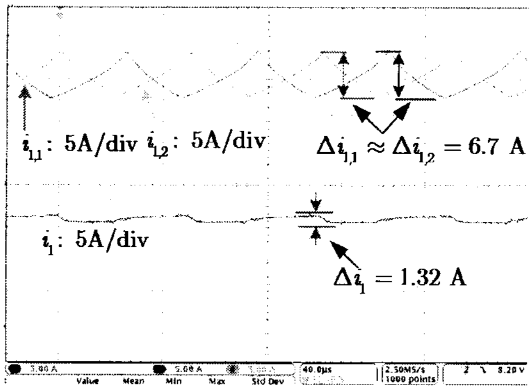

Fig. 8. Inductor current of each phase and the input current when p_{Load} = 390 W.

Acknowledgements

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