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Current-fed full-bridge DC-DC converter with nonlinear control scheme

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***Abstract*—This paper presents a control algorithm for dealing with the constraints of energy power source and a current-fed full-bridge converter. The advantages of this control scheme include transient and steady-state responses and robustness. The prototype of 26 V/100 V 250 W and its controller were implemented. A dSPACE DS1104 was used to implement the outer control loop by using flatness system's properties. An analog control card was employed as an inner control loop by using hysteresis-based PWM. The validation of the proposed control was demonstrated through experiment results.**

Keywords-renewable energy; flatness system; hysteresis; PWM; robustness

I. INTRODUCTION

Renewable energy has been regarded as a high potential energy source for today and tomorrow. It brings us not only abundant of fuels but also environment friendly. To generate electricity, one can harvest energy directly from the sun using solar cells or photovoltaic cells. Fuel cell is another energy source producing electricity using oxygen from air and hydrogen from clean source [1]. As the voltage level of the renewable energy sources are quite low, to step the voltage up to the desirable level, a DC-DC converter is commonly utilized [2]-[3]. Several converters have been proposed and presented in literatures including control techniques using both linear and nonlinear analysis tools [2]-[6].

Since both of the mentioned energy sources prefer sourcing smooth output current, this mean that the output current drawn by a converter should have low ripple current. For this situation, boost converter is the first converter that researchers think about. It can step the output voltage up about 3-4 times higher than its input [3]. However, its limitation is the losses in the converter. If one needs high voltage step-up ratio, a cascade converter which is using two or more converters connected together, is an option. But this might bring down the overall efficiency. Its input current ripple depends on switching frequency, input voltage, duty cycle and inductance. To decrease the ripple current and also increase high current capability, an interleaved technique has been commonly used [2], [6]. In this paper, we consider a current-fed full-bridge converter, which gives high voltage gain ratio. It can be used as a converter cell in an interleaved converter. A control method based on nonlinear control technique has been proposed and experimented.

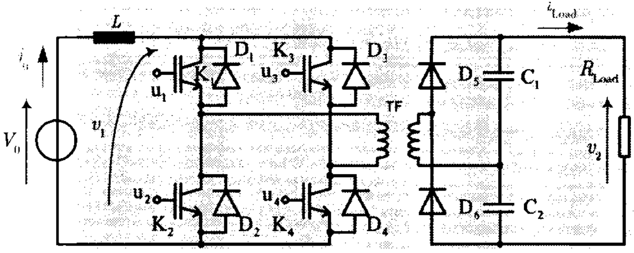

Figure 1. Current-fed full-bridge converter

II. CURRENT-FED FULL-BRIDGE CONVERTER

Current-fed converter is shown in Fig. 1, this kind of converter has reputation in low input ripple current and high voltage gain. Moreover, using high frequency transformer, we gain both small footprint and galvanic isolation. At the output section of this converter, a full-wave rectifier can be used. However, one can use a voltage doublers cell instead of the conventional rectifier to double the voltage providing by the secondary transformer winding. In this paper, we have studied the voltage doublers converter. The theoretical waveforms of the converter have been depicted in Fig. 2.

A. Converter model

An easy way to study this converter is to transform them to a simple boost converter shown in Fig. 3. Suppose that all devices used in the converter are ideal. In Fig. 2, β is the equivalent duty cycle. This duty cycle is the same as in conventional boost converter occurring when both control signals of the upper and lower switches conduct at the same time. Then, the input current ripple of this converter can be found in the same way as for a boost converter which is detailed in (1). It depends on the input voltage V_0, inductance L, switching frequency f, duty cycle:

$$\Delta i_0 = \beta \frac{V_0}{Lf_{eq}};\ \forall\ \beta = \alpha_{eq} > 0 \qquad (1)$$

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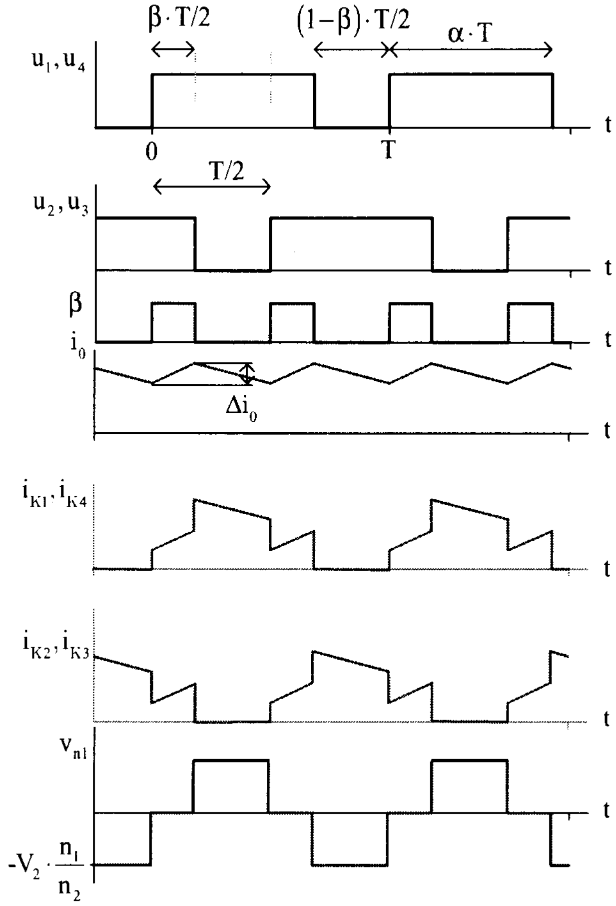

Figure 2. Key waveforms of current-fed full-bridge converter

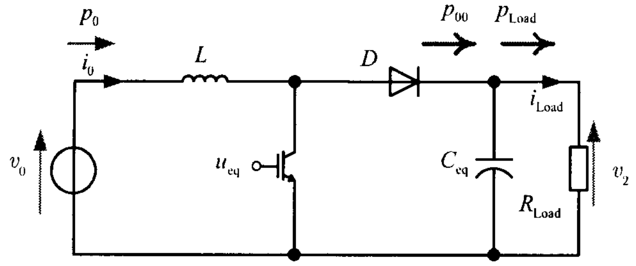

Figure 3. Equivalent boost converter

where β is the equivalent duty cycle α_{eq} and f_{eq} is equivalent switching frequency depicted in Fig. 2.

The equivalent frequency is doubled up as the switching frequency $f_s = 1/T$. When the converter operates under continuous conduction mode (CCM) where the input current never fall down to zero. The voltage gain is given by:

$$\frac{V_0}{V_1} = \frac{n_1}{n_2}\frac{1}{\left(1-2\beta\right)} \tag{2}$$

III. CONTROL ALGORITM

To control this converter, we proposed to use a two-control loop approach where the inner loop is the inductor current and the outer loop is the energy stored in the output capacitor, which is an image of the output voltage.

A. Inner current loop

As regard to robustness of the controlled system and fixed switching frequency behavior, a current controller with hysteresis-based is used [7]. To do this, a PI controller should be defined first:

$$S_0 = k_p\left(i_0 - I_{REF}\right) + \frac{k_p}{T_i}\int (i_0 - I_{REF})dt \tag{3}$$

where i_0 is the inductor current and I_{REF} is the referenced current providing by the outer loop. k_p and T_i are parameters. The complete current controller diagram is shown in Fig. 4. A stable operation domain depending on the control paramerters including A and B_h where k_p =1 can be found in [7].

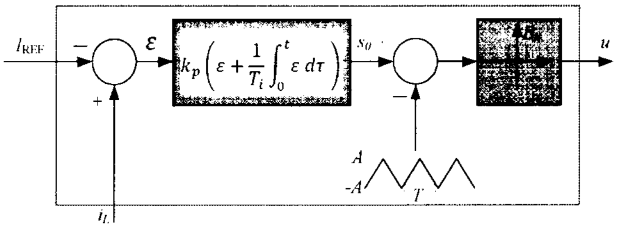

Figure 4. Hysteresis-based PWM current controller

B. Outer voltage loop

As mentioned earlier, the energy stored in the output capacitors will be controlled at a certain value which means that the output voltage is also constant. The energy stored in the capacitor can be found as:

$$y = \frac{1}{2}C_{eq}v_2^2 \tag{4}$$

where $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$.

Obviously, one can find the state variable, which is the output voltage in function of that energy y:

$$x = v_2 = \sqrt{2y / C_{eq}} = \phi_x\left(y\right) \tag{5}$$

The variation of energy in the capacitor C_{eq} is

$$\dot{y} = p_{00} - p_{Load} \tag{6}$$

Considering power losses in the converter as power losses in a fictive series resistor r_s, we can find the power supplied by the energy source by:

$$\dot{y} = p_0 - \left(\frac{p_0}{v_0}\right)^2 r_s - p_{Load} \tag{7}$$

This leads to

$$p_0 = 2P_{0\max} \cdot \left(1 - \sqrt{1 - \frac{\left(2y / C_{eq}\right) / R_{\mathrm{Loadeq}} + \dot{y}}{P_{0\max}}}\right) = \phi_u\left(y, \dot{y}\right) \tag{8}$$

Where $P_{0\mathrm{max}}$ is the maximum power, which can be supplied by the source verified $P_{0\max} = V_0^{\,2} / 4r_s$.

Regarding (4), (5) and (8), we found that if we have chosen y as the flat output, the state variable x can be found in the function of the chosen flat output. Then we can also find the command input u in a function of the flat output and its time derivative. This shows that the considered system is differential flatness system [8]. Once, we prove that the system is flat, we can plan the energy reference. To prevent an excessive capacitor current, we have selected the response of the reference like a second order response with unity damping factor. The time response of this reference for a step function is given by:

$$y_{\mathrm{REF}}(t) = y_{\mathrm{REF},final} \cdot \left(\left(1 - e^{-\frac{t}{\tau}}\right) - t \cdot e^{-\frac{t}{\tau}} / \tau\right) \tag{9}$$

where the energy reference rises from zero until $y_{\mathrm{REF},final}$.

To ensure that the flat output tracks well its reference, we have used a control law with a fictitious control υ:

$$\upsilon = \dot{y} - \dot{y}_{\mathrm{REF}} + 2\zeta\omega_n\left(y - y_{\mathrm{REF}}\right) + \omega_n^{\,2}\int\left(y - y_{\mathrm{REF}}\right)d\tau = 0 \tag{10}$$

The complete control block diagram is shown in Fig. 5.

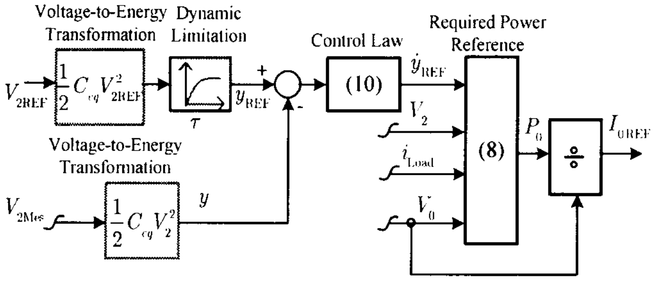

Figure 5. Control block diagram

IV. EXPERIMENTAL RESULTS

To validate the proposed control method, a small power scale test bench has been implemented in laboratory (see Fig. 6). A programmable power supply has been used inplace of the renewable energy source. Four MOSFETs (IRFP4232PbF 250 V 42 A), two diodes (HFA25PB60PBF 600 V 25 A) and two electrolytic capacitors (1000 μF 450 V) were used. An inductor of 0.3 mH and a transformer with turn ratio of 1:6 was built on the bobbin attached to the ferrite magnetic core. The following parameters are used in this paper: $k_p = 1$, $T_i = 0.2$ ms, $A = 12$ V, $B_h = 0.1$, $\omega_h = 1000$ rad·s^{-1}, $\zeta = 0.707$, $\tau = 1$ s. Three phases of experiment have been conducted. Firstly, a start-up behavior will be test and shown in Fig. 7 where two value of the time constant τ have been used.

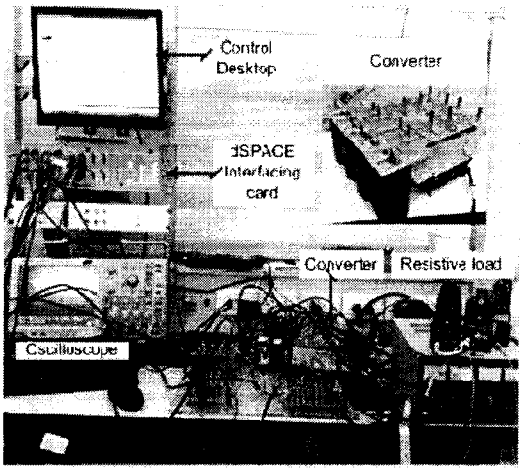

Figure 6. Experimental setup

On the top figure, τ =1s, whereas on the bottom one, τ = 10 s. The flat output corresponding to its image (the output voltage) tracks well its reference for different time constant demonstrating advantages of using flatness properties in the control loop. Fig. 8 shows the tracking behavior when the flat output reference is changed as the second test. Like in the previous test, the flat output tracks its reference perfectly both in transient and steady-state operation.

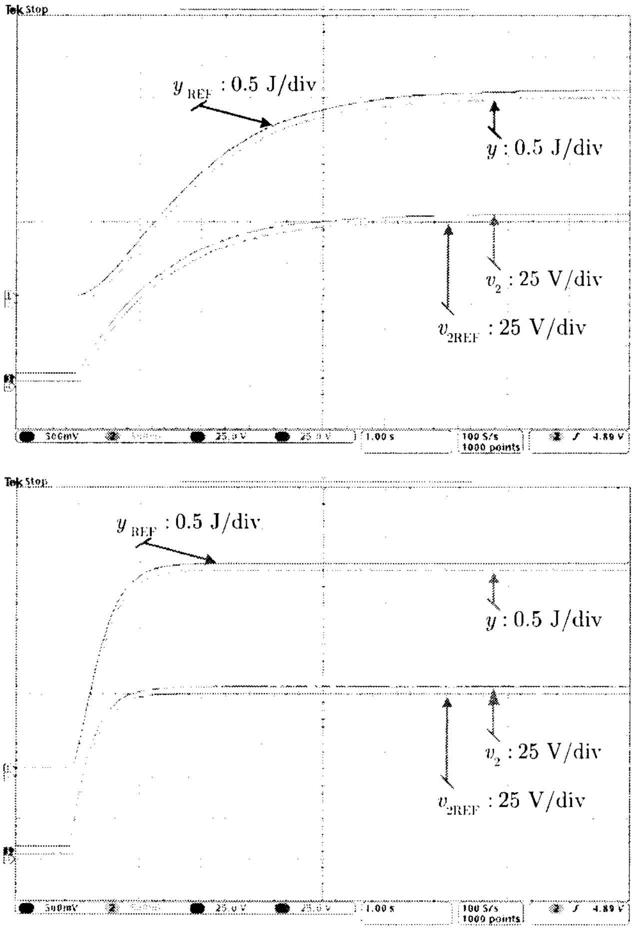

Figure 7. Start-up response of the proposed system: (top) τ = 1 s, (bottom) τ = 10 s

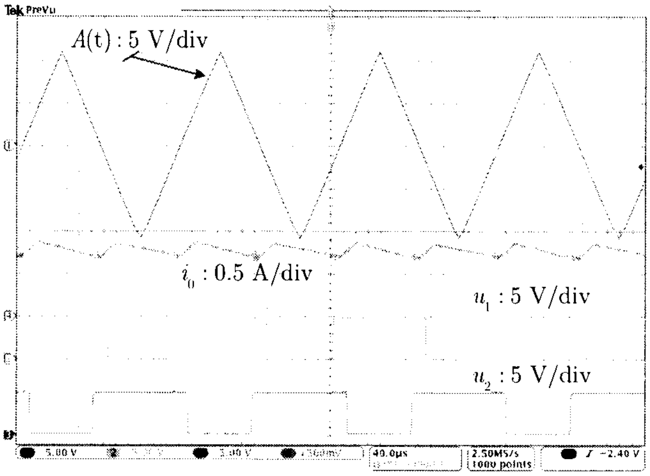

Figure 8. Steady-state waveforms of the system

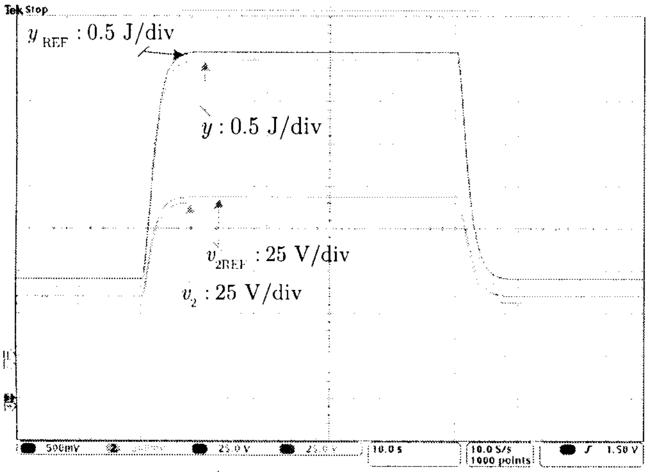

Figure 9. Flat output tracking response of the proposed system with change in the output voltage reference v_2

Fig. 9 depicts the third test, which is the regulation problem when the resistive load has been stepped from 10 W to 300 W by the help of a small circuit breaker (CB). There is some perturbation on the flat output signal and then it can return back to the setting point. This phenomenon has also occurred on the output voltage detailed in the red circle. In the green circle, an arc occurs when CB is opening. The settling time of the flat output depends on the bandwidth of the energy control loop.

To show the robustness property, an inductor of 0.3 mH (100% of the inductance L) has been connected in series to the inductor L. The response of the system is shown in Fig. 10. Despite inductance was changed, the flat output can track its reference.

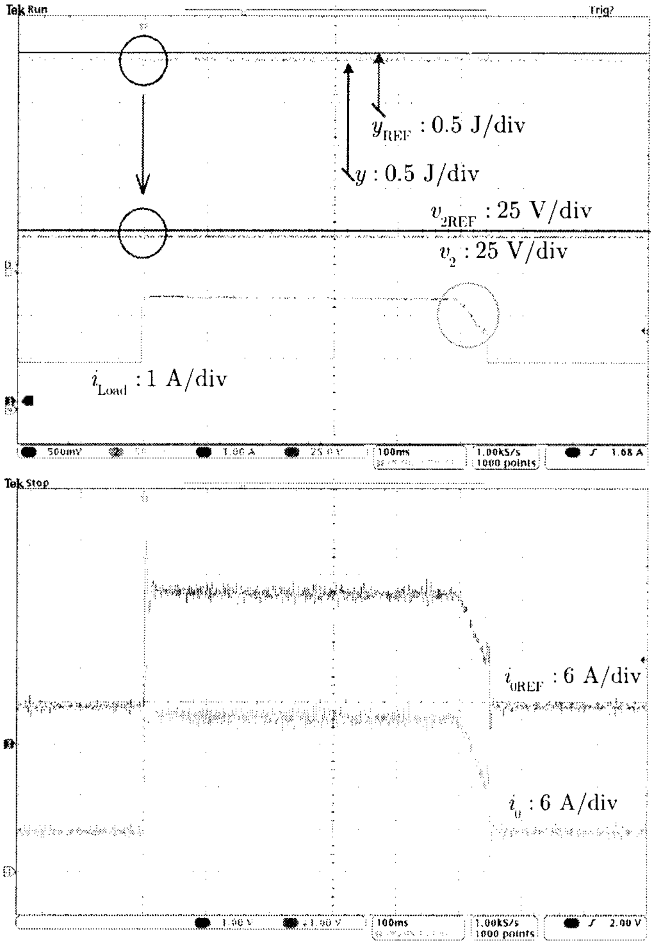

Figure 10. Experimental results for step change in load from 10 W to 300 W: (top) flat output y and its reference, the output voltage v_2 and its reference and the load current i_{Load}, (bottom) the input current and its reference

V. CONCLUSION

Generating electricity from renewable energy source is very important. To draw electricity from that source, we might need switching converters to interface between the source and the end users. The current-fed full-bridge converter has low input current ripple and high voltage gain properties and it is suitable for using as a bridge from the renewable source to load. With nonlinear controller, the dynamics properties do not depend on an operating point. Moreover, robustness is also gained. The proposed control method demonstrates the effectiveness through the experimental results.

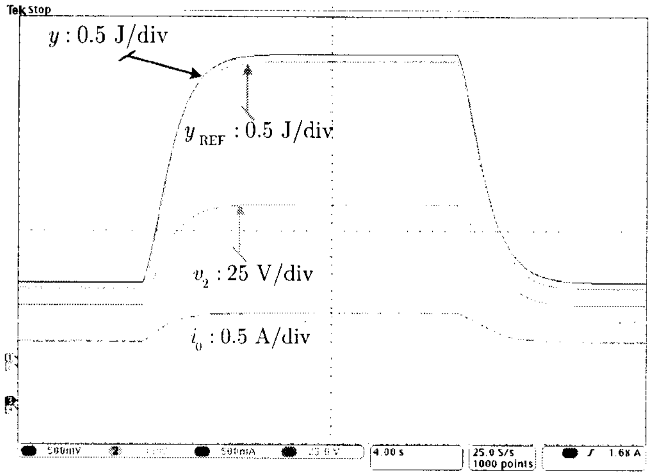

Figure 11. Robustness of the system against change of inductance L of 100%

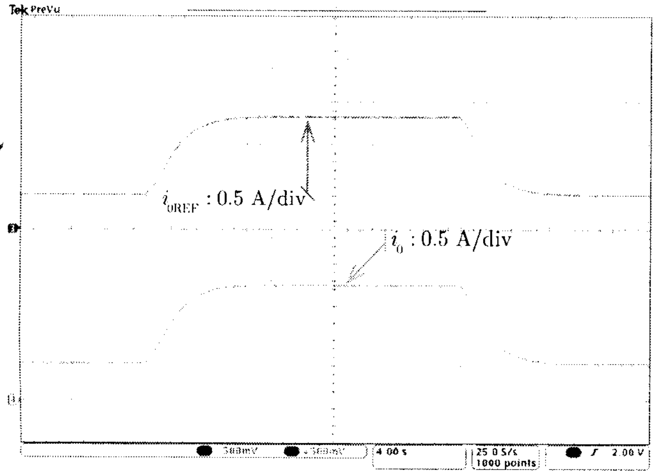

Figure 12. Robustness of the system against 100% change of inductance L

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