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Abstract—Interleaved boost converters are useful in renewable energy applications like photovoltaics (PV) and fuel cells (FC). In this paper we investigate the nonlinear behavior of an interleaved boost converter fed from a PV source. In this system, at a critical parameter value the normal periodic orbit loses stability through a Neimark-Sacker bifurcation and a torus is created. We demonstrate that the torus undergoes folding when it hits one of the switching borders and is deformed when it grazes another border. Finally we observe that when the converter is fed by PV the system tends to be less stable.

1. Introduction

The area of nonlinear dynamics of power electronics has attracted a lot of interest [1–4] and various bifurcation phenomena have been studied. Most notably the loss of stability through a fast or slow scale bifurcation has been thoroughly studied and analyzed [5]. The interaction of these two bifurcations has also been reported in [6] and the destruction of the torus through various bifurcations has been observed in [7, 8]. Most of this work is focused on “simple” dc-dc converters and little work has been done in parallel connected converters that are used when high power applications are required [9–11]. In this paper we investigate the nonlinear behavior of parallel connected power converters and more specifically we study a 3-leg interleaved boost converter. Aiming at renewable energy application, we study the effect of PVs on the nonlinear behavior of the converter.

2. System Description

2.1. Interleaved boost converter

A three-leg parallel connected converter supplied from a Renewable Energy Source (RES) is shown in Fig 1. To operate the converter in interleaved mode each switch is controlled by a separate peak current controller with a phase delayed clock signal. The phase lag is $T/3$s for the second controller and $2T/3$s for the third.

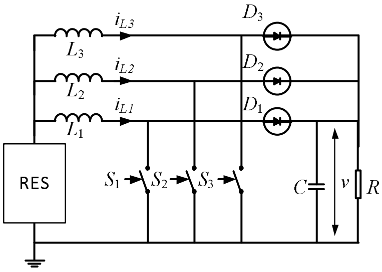

Figure 1: Schematic diagram of a three-leg interleaved boost converter. The nominal parameter values taken in this study are $V_{\text{in}} = 5$V, $R = 20\Omega$, $L = 1.5\mu$H, $C = 10\mu$F, $T = 100\mu$s.

2.2. Photovoltaic Panel

The voltage output of the RES depends on the current drawn by the converter and this may influence its behavior. The current depended output of the RES is shown in Fig. 2 for a typical PV.

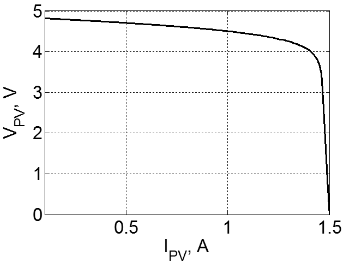

Figure 2: V-I characteristics of a typical PV. The parameters of the PV are: $R_s = 0.1\Omega; R_{sh} = 100\Omega; T_e = 300$K, $I_o = 10^{-10}$A; $A = 3.8647$.

3. Bifurcation study

The nonlinear behavior of the converter with and without the PV is shown in Fig. 3, where it is clear that the main qualitative properties of the system remain the same. The only difference is that the in system with the PV the instability occurs at a lower value of the demanded current. This is explained by the fact that by increasing the current drawn from the PV, the input voltage drops (see Fig. 2). As the basic nonlinear phenomena are the same in both cases, only the system with the constant supply will be thoroughly investigated in this paper.

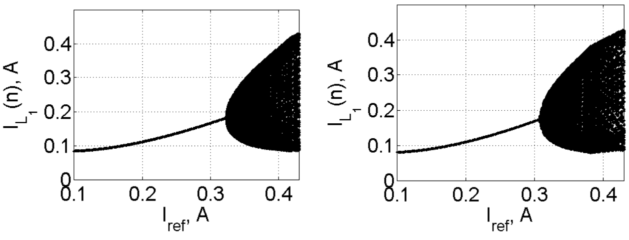

Figure 3: Bifurcation diagram of the interleaved boost converter, (a) with constant input source, and (b) fed by a PV.

The period-1 waveform of the converter is shown in Fig. 4 for five different duty cycles, also showing the values of the currents sampled with respect to the first clock. The orbits shown in the figure can be stable or unstable (depending on the value of the duty cycle). As symmetrical phases are considered, the current in each leg will be exactly the same but delayed with respect to the first phase. The delay of the second phase is T/3 seconds and of the third phase 2T/3 seconds. This implies that whatever happens in the first current at $t = t_1$ will also happen to the 2nd phase at $t = t_1 + T/3$ and to the third phase at $t = t_1 + 2T/3$. From Fig. 4, it is clear that the sample of the first current will always be smaller than the other two samples. Also when the duty cycle becomes 1/3 the sample of the third current will be equal to I_{ref} and when the duty cycle is 2/3 the samples of the 2nd current will be equal to I_{ref}. Finally, if the duty cycle tends to 1, the sampled current of the first phase will tend to hit the border I_{ref}. When this happens, the duty cycle of the next clock will be 0.

The nominal period 1 orbit loses stability though a Neimark-Sacker bifurcation and a torus is created when $I_{\text{ref}} = 0.323$A (Fig. 5). An interesting property of this torus is that it also has the properties of a period 2 orbit, i.e., the eigenvalues of the unstable period-1 orbit have real part very close to -1. This explains the fact that the points on the torus close to the bifurcation have an angle of almost 180 degrees. The interleaving operation of the converter also imposes a symmetry in the orbit. When the period 1 orbit is destroyed through a slow scale bifurcation, the torus that is created inherits the symmetry of the 3 currents, but now they are out of phase by $T_{\text{torus}}/3$ seconds where T_{torus} is the time that is required for a complete rotation on the torus. For example in Fig. 8 we need 55 samples or $t_{\text{torus}} = 55 \times T = 0.0055$ seconds and the phase shifts are $55 \times T/3$ and $2 \times 55 \times T/3$ for the other two phases.

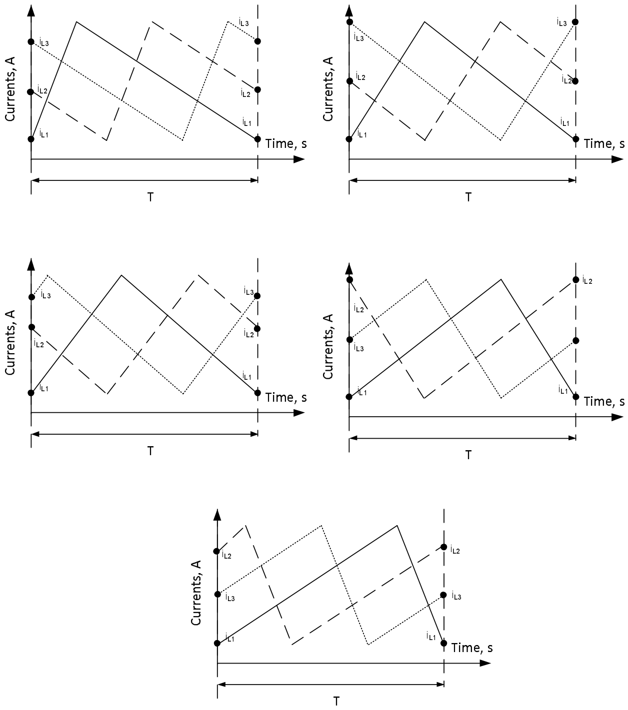

Figure 4: Time response of the three currents for D=0.2, D=1/3, D=0.4, D=2/3, D=0.8.

As the parameter (the reference current) is increased, the torus undergoes a series of deformations. When $I_{\text{ref}} = 0.3255$A and the duty cycle becomes 1/3, the sampled third current hits the border $i_{L_3} = I_{\text{ref}}$; this causes the first folding in the state space (Fig. 6). When the demanded current is further increased (approximately $I_{\text{ref}} = 0.34A$, D=2/3) we observe another folding (Fig. 7) due to now the fact that the sampled 2nd current hits the border $i_{L_2} = I_{\text{ref}}$. When $I_{\text{ref}} = 0.42$A there is a clock cycle on the torus with a duty cycle close to 1, in this case we see that the sampled current of the first leg is very close to the border $i_{L_1} = I_{\text{ref}}$. For $I_{\text{ref}} = 0.425$A there are clock cycles on the torus with duty cycle 1, which implies that we have a border collision. In the state space this is shown as a grazing of the border $i_{L_1} = I_{\text{ref}}$. For $I_{\text{ref}} = 0.44A$ in Fig. 8 we see the full deformation (wobblings) due to the grazing. The two symmetries (real eigenvalue close to -1 and interleaving operation) explain the form of the torus. When the torus grazes the border, there is a deformation seen in the area D of Fig. 8a. As the angle of rotation is close to 180 degrees this deformation is mapped to the area B. Now, the period of the torus is 55 samples and therefore the area D is mapped to A after $2 \times 55/3$ samples. Similarly for Fig. 8b the area D is mapped to C after 55/3 samples and to B due to the angle of rotation.

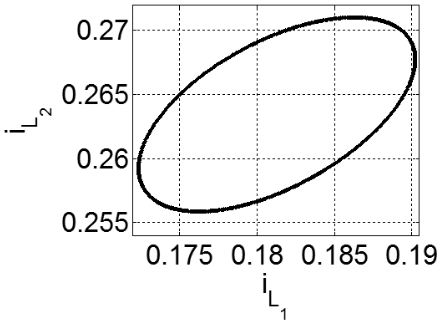

Figure 5: The torus for $I_{\text{ref}} = 0.3231$A

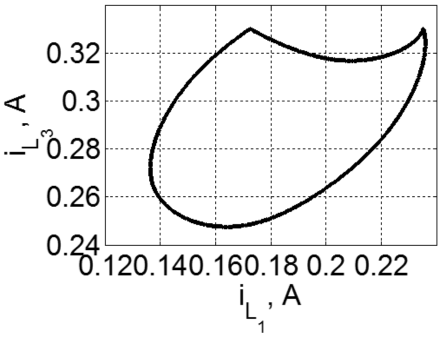

Figure 6: The torus after the first folding, $I_{\text{ref}} = 0.33$A

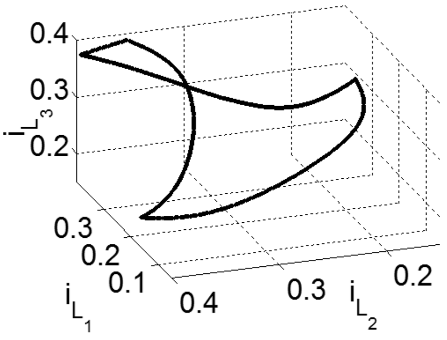

Figure 7: The torus after the first folding, $I_{\text{ref}} = 0.4$A

4. Conclusions

In this paper we considered an interleaved boost converter with three inductor-switch legs and one capacitor. The current mode control is applied on each leg, with the respective clocks out of phase with each other by $T/3$. We show that such a converter may lose stability as the demanded current increases beyond a critical value, and that a torus develops in the state space following the bifurcation. If the converter is fed from a renewable energy source like a photovoltaic panel, the bifurcation occurs at a smaller value of the demanded current, but otherwise the dynamical behaviours are qualitatively the same for a converter fed from a PV panel and that fed from a constant voltage source. We show that at an even higher value of the demanded current, the torus undergoes folds when it grazes the switching manifolds in the discrete-time state space.

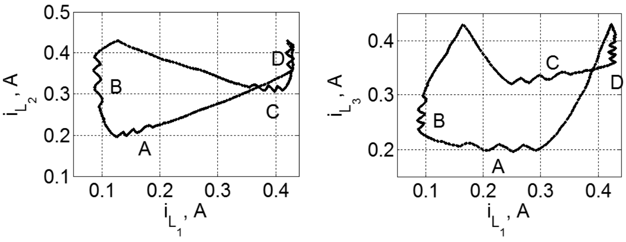

Figure 8: The torus after the grazing, $I_{\text{ref}} = 0.43$A, from different perspectives.

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