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Experimental Study of Parallel-Connected DC-DC Buck-Boost Converters FPGA Chaos Controlled

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***Abstract* — Chaos control is used to design a controller that is able to eliminat*e* the chaotic behavior of nonlinear dynamic systems that experience such phenomena. This paper discuss the use of the FPGA as a controller of a parallel-connected DC-DC buck-boost converter, the goal of this paper is to build a controller that is capable of controlling the output current of a photovoltaic cells and minimize the effect of the module buck-boost converter chaotic behavior on the output voltage. To achieve this goal this paper presents two different methods, FPGA control the duty cycle and the frequency of the output controlling signal, this technique is done through software (FPGA code), and a delayed feedback control scheme in a module converter in the continuous-current conduction mode (CCM) using MATLAB/SIMULINK simulation. Thus, this paper shows the FPGA capabilities in the power industry and it’s specifies a guideline to overcome some of the obstacles when dealing with an FPGA as a buck-boost converter controller, and MATLAB/SIMULINK simulation results show the effectiveness and robustness of the scheme.**

I. INTRODUCTION

DC-DC converters are common and they deliver power at different voltage levels. They are used in many applications, such as renewable energy systems. In reality the converter input might be a photovoltaic (PV) array that charges a battery, the load. Fixed switching rate buck and boost converters have all been shown to exhibit chaotic behavior within certain operating conditions [1-8]. Converters are usually designed so that in its normal operating region it functions in a stable manner. Outside of these conditions the converter can experience period doubling bifurcations (forking) that can develop into chaos (unpredictability). When chaotic behavior occurs, it can cause additional losses, noise and even destroy the electronics. Chaotic behavior is therefore extremely undesirable and a requirement exists to understand this behavior and control it.

The connection of multi-input/multi-output DC-DC converters in parallel, with the load shared between modules when be connected to multi-input/multi-output PV modules, reduces current stress on the switching devices and increases system reliability. However, despite the growing popularity of these modular converters, their bifurcation phenomena have rarely been studied to see the effect of bifurcation and chaotic behavior on the PV arrays.

This paper investigates the control of chaotic behavior in a two-module parallel input/parallel-output buck-boost converter operating under a peak current-mode control scheme using a delayed feedback control strategy, which is based on the idea of stabilization of unstable periodic orbits that exist in the chaotic attractor [9], where each module has its own current feedback loop. The converter consists of two similar buck-boost circuits operating in the CCM. A MATLAB/SIMULINK model for the converter was developed. The goal of this paper also is to control this module buck-boost converter current using the Field Programmable Gate Array (FPGA) technology in order to use it in a smart grid system.

The problem with PV’s that the amount of energy (current level) produced depends on the amount of light hitting them, but to connect them to the grid this voltage (power) level must be stabilized and stepped up (to be compatible with the inverter and other circuits and to ensure that maximum power is delivered to the load). Generally, PV’s are designed to operate at a voltage of 12-24V but to improve the overall system efficiency the voltage has to be stepped up and kept at a stable level, this level is going to be the input for the FPGA, and the FPGA will keep adjusting the PWM output that controls the DC-DC buck-boost converter MOSFET to achieve the desirable voltage level.

This paper investigates the chaotic behavior of the modular buck-boost converter and suggests a solution to eliminate this phenomenon using the Field Programmable Gate Array (FPGA) embedded system rather than ATMEL [8].

II. BIFURCATION AND CHAOS

Bifurcation is a route to chaos for many non-linear systems. The chaos can appear quickly or after several bifurcations, depending on the system and its parameters. Bifurcations are when the expected result forks and has two possibilities. Through period doubling the expected result can have several possibilities.

In bifurcation problems, in addition to state variables, there are control parameters. The relationship between any of these control parameters and any state variable is called the state-control space. In this space, locations at which bifurcations occur are called bifurcation points. Bifurcations of an equilibrium or fixed-point solution are classified as either static bifurcations, such as saddle-node, pitch fork, or trans-critical bifurcations; or as dynamic bifurcations which are also known as the Hopf bifurcation that exhibits periodic solutions. For the fixed-point solutions, the local stability of the system is determined from the eigenvalues of the Jacobian matrix of the

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linearized system. On the other hand, with periodic-solutions, the system stability depends on what is known as the Floquet theory and the eigenvalues of the Monodromy matrix that are known in the literature as Floquet or characteristic multipliers. The types of bifurcation are determined from the manner in which the Floquet multipliers leave the unit circle.

Chaos is the unpredictability in a system. The theory was first developed in 1960 by Lorenz. It is possible to experience chaos in many systems and it can be investigated in converters by adjusting the converter pulse width modulation (PWM). Chaos is an undesirable effect and can cause additional losses, noise, other unwanted outputs and possibly the catastrophic failure of the converter or its connected electronics.

III. MATHEMATICAL MODELLING

A simplified diagram for the proposed converter is shown in Fig. 1. It consists of two peak current-mode controlled DC-DC buck-boost converters whose outputs are connected in parallel to feed a common resistive load. Each converter has its own current feedback loop comprising a comparator and a flip-flop. Each comparator compares its respective peak inductor current with a reference value, to determine the on-time of the switch using the most popular FPGA kits in the academic world which is the Spartan 3E Starter Kit.

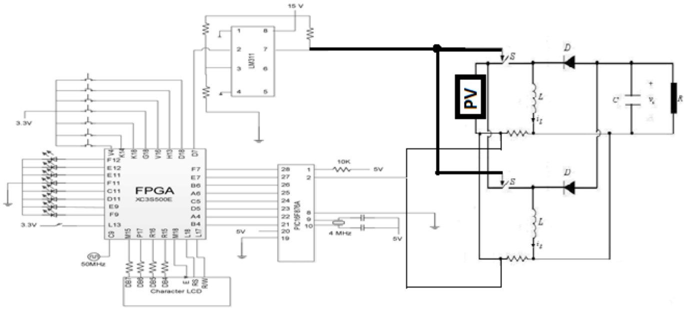

Fig. 1. Simplified circuit diagram for the two-module converter

The program will compare the actual current of the system with the desired current (reference current) entered to the FPGA and will decide whether to increase or decrees the duty cycle. Notice that the software will never achieve a certain duty cycle to a certain current; instead it will keep changing the duty cycle in an infinite loop to match the actual currents and the reference current. Where the actual currents i_{L1} and i_{L2} respectively the inductor currents for L_1 and L_2.

IV. MATLAB CODE & MATLAB/SIMULINK SIMULATION

A MATLAB/SIMULINK model was developed based on the system equations (1), and a MATLAB code written for the two module under the same conditions to compare the results at the critical points when the system bifurcates from period to other with period-doubling bifurcation as expected.

$$\begin{aligned}
\frac{di_{L1}}{dt} &= \frac{1}{L_1}[v_{in} - v_C(u_{S1} - 1)] \\
\frac{di_{L2}}{dt} &= \frac{1}{L_2}[v_{in} - v_C(u_{S2} - 1)] \qquad (1) \\
\frac{dv_C}{dt} &= \frac{1}{C}[-\frac{v_C}{R} + i_{L1}(1 - u_{S1}) + i_{L2}(1 - u_{S2})]
\end{aligned}$$

Where u_{S1} and u_{S2} take the value 0 or 1 depending on whether the switches 1 or 2 are closed or open. The structure of the MATLAB/SIMULINK model is shown in Fig. 2.

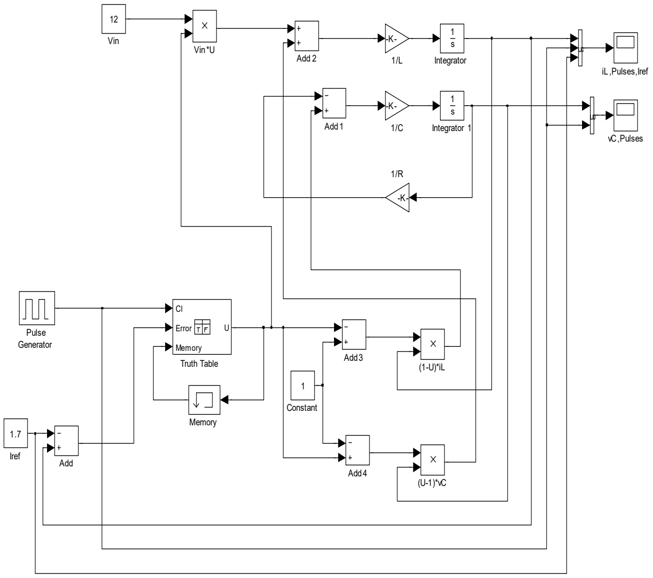

Fig. 2. SIMULINK open-loop model for the modular converter

V. PERFORMANCE ANALYSIS

To compare all the time-waveform results, the bifurcation diagram for the system given in Fig. 3 shows the inductor current as a state variable with the reference current as a control parameter. The chosen of the reference current as a control parameter rather than the input voltage or the load resistance is just for comparison with the time wave forms. It can be seen that the critical points are very close to the results obtained by FPGA and MATLAB/SIMULINK simulation.

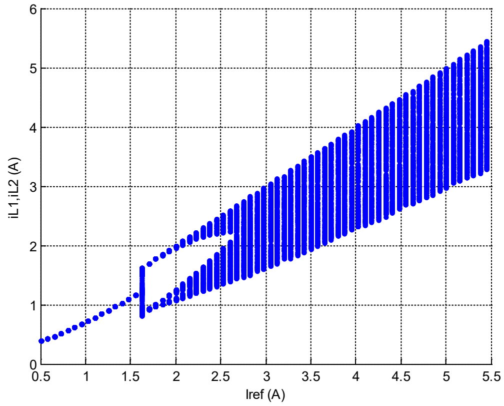

Fig. 3. Bifurcation diagram for each converter in the two-module

The converter is chaotic ($i_{L1}+i_{L2}$) at I_{ref}=5A with a 22 ohm load resistance and an input voltage of 12V as shown in Fig. 4. Chaos that occurs in a system at this case can have dramatic effects. It can reduce the efficiency, causes the system to be unreliable, be the source of a failing system or produce unexpected dangerous events in linked systems. Load changes, noise and increasing the switching frequency can all cause the PWM controlled converter to exhibit bifurcations and ultimately chaos.

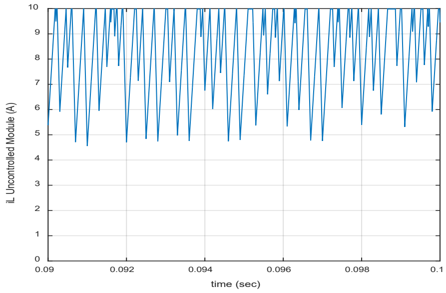

Fig. 4. "Uncontrolled Chaotic" at I_{ref} = 5A

VI. CONTROL OF CHAOS

Pyragas [9] has suggested that chaotic behavior may be eliminated from the system if one applies the delayed feedback control. The feedback control force, applied to the system is the difference between the current value of some system variable, and its value τ seconds previously, multiplied by a constant *K*, where *K* is the feedback strength. The idea behind the scheme relies on the fact that a skeleton of a chaotic attractor is formed by an infinite set of unstable periodic orbits with different periods. If the value of the time delay τ is exactly equal to the period *T* of one of the orbits, then at the appropriate values of *K*, the orbit can become stable and chaos will be eliminated. In simple terms, an unstable periodic orbits embedded in the chaotic attractor is selected then control is used to fix this orbit through small changes in the parameters. When the chaos passes sufficiently close to the orbit it is made linear. As the controller *is* connected to the open-loop model, the inductor

$$i_L(t) = I_{ref} - K[i_L(t-\tau) - i_L(t)] \tag{2}$$

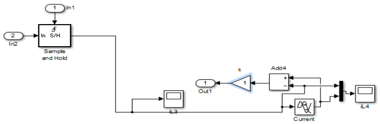

Fig. 5. SIMULINK closed-model for a modular converter

As the controller connected to the open-loop model, the inductor current at switch turn-on now does not have many values and the periodic regime is stable as shown in Fig. 6.

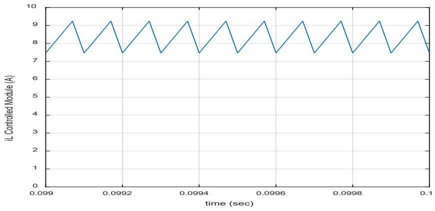

Fig. 6. "Controlled Chaotic" at I_{ref} = 5A delayed feedback controller

The results of the FPGA even at rated values of the system the current was very stable. It was mind baffling, the software have chosen one or two frequencies for its controlling operation without being programmed to do so as shown in Fig. 7.

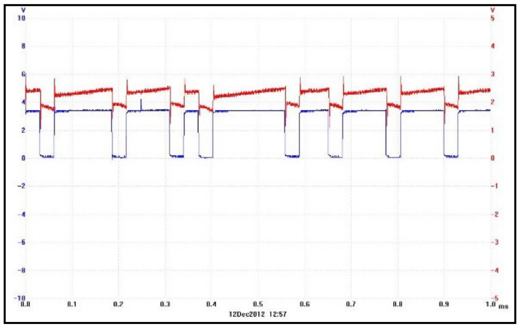

Fig. 7. "Controlled Chaotic" at I_{ref} = 5A FPGA controller

It is clear that the periodic regime observed is stable. The waveforms have the desired frequency of 10 kHz ("period-1" cycles) at I_{ref} = 5A.

VII. CONCLUSION

Multi-input/multi-output DC-DC buck-boost converters associated with PV modules will be working perfectly if the selection of the controller gain chosen precisely. The simulated time waveforms for $i_L(t)$ at I_{ref} = 5A with the converter connected to the delayed current feedback (the control circuit) and FPGA showed the converter is operating in a "period-1" mode as required. The study shows the effectiveness of the designed controllers. Smart and fast controller for smart grids has the ability to enhance the main grid capability and efficiency and the FPGA is a great choice for a controller because of its high frequency and multiple I/O’s and parallel processing capabilities.

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