International Conference on Control, Engineering & Information Technology (CEIT'14)
Proceedings - Copyright IPCO-2014
ISSN 2356-5608

HIL simulation approach for a multicellular converter

Salwa BEN SAID
Salwa.bensaid.enit.rnu.tn

Kamel BEN SAAD
kamel.bensaad.enit.rnu.tn

Mohamed BENREJEB
Mohamed.benrejeb.enit.rnu.tn

Laboratoire de Recherche LA.R.A Automatique,
Ecole Nationale d'Ingénieurs de Tunis, BP 37, le Belvédère, Tunis 1002, TUNISIA
Université de Tunis EL Manar

Abstract— **This paper presents Hardware In the Loop (HIL) simulation approach for a multicellular converter control validation.**

As multicellular converters are used generally for high power application, some safety measures must be taken before the experimental tests. Thus, HIL simulation can be a solution.
HIL simulations reduce development cycle, increase efficiency, improves reliability and safety of power electronics systems and converter tests. A closed loop control is presented in this paper for the studied converter. It aims to give it more robustness against some parameters variations. The proposed control approach is validated with success by HIL simulation approach.

Index Terms—Multicellular converter, Control law validation, Hardware In the Loop (HIL), IP control, robustness.

I. INTRODUCTION

A multicellular converter is a system of energy conversion, based on a series-association of elementary commutation cells. It allows the distribution of the voltage constraints among series-connected switches. Multicellular converters are characterized by their modularity and high efficiency.
Thus, they are more and more used in industrial application, especially for high power applications. However, the major drawback of this kind of converter is their control complexity.
To improve the performances of multicellular converters there are two solutions. The first one consists into improving the structure and the technology of the semiconductor power components. The second is based on control solutions.
Nowadays, electronic control circuits are so efficient that they allow the implementation of sophisticated control laws. Thus, to insure the robustness of the switching converters, closed loop control solutions are more and more used.

Generally, after the simulation tests a control law is validated experimentally. This approach presents some dangers. Indeed, test fails can be costly and dangerous. Thus, the design and the validation of control laws for power electronics converters must follow a methodology allowing the rapid design prototyping and safe tests.

Hardware-in-the-loop (HIL) is a simulation technique used in the development and the test of complex real-time embedded systems [1]. HIL simulation provides an effective platform by incorporating the controlled plant to the test platform.
The controlled system is integrated in test and development by adding a mathematical model representing all related controlled system dynamics [3].
HIL Simulation is more and more applied for Power Electronics systems. Such approach reduces the development cycle, increases efficiency, improve reliability and safety. Moreover, it prevents costly and dangerous failures [4].

This paper is organized as follows. In section 2 some HIL principles are presented. After the presentation of the model and the structure of the studied multicellular converter in section 3, an open loop control and a closed loop control are presented in section 4. The proposed HIL simulation approach results described in the section 5.

II. HIL SIMULATION PRINCIPLES

Figure 1 presents the development cycle, called the V diagram, design which includes the following five steps [2]:

- Modeling and design
- Model In the Loop (MIL)
- Software In the Loop (SIL)
- Hardware In the Loop (HIL)
- Experimental tests

The left part and the right part of the V diagram represent respectively the design and the test steps.

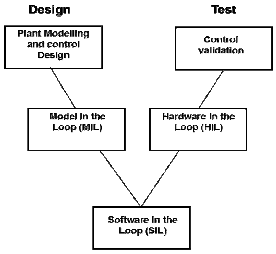


Figure 1. V diagram

MIL consists into simulating the control law and the plant in the same simulation environment. Such simulation approach allows the development of the control algorithm, figure 2.

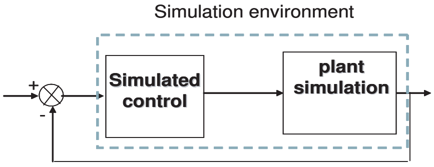


Figure 2. Model In the Loop

After the MIL simulation, the control law is translated into compiled programming language. This simulation step, called SIL, allows the controller program tests, figure 3.

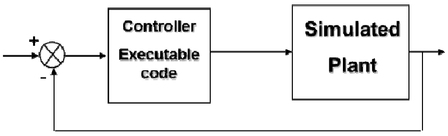


Figure 3. Software In the Loop

HIL simulation requires the real control component (controller) and a real time platform for the simulation of the controlled plant, figure 4. It is the last step before the experimental tests.

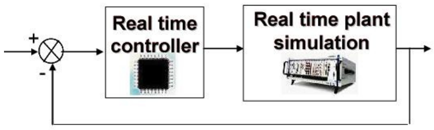


Figure 4. Hardware In the Loop

HIL simulation presents some benefits. Indeed, it: prevents costly and dangerous failures. Moreover, allows the design and the tests of the control law without the presence of the real plant.

III. STUDIED MULTICELLULAR CONVERTER MODEL AND OPEN LOOP CONTROL

A. Multicellular converter Structure

The general structure of the studied multicellular converter is presented in figure 5. It is composed of p-cells. Each cell contains two complementary power electronics components controlled by a binary switch.

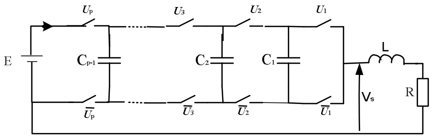


Figure 5. General structure of the multicellular converter

In the multi cellular converter, the cells are associated in series with a RL load and the cells separated by capacitors that can be considered as continuous voltage sources [3][2]. Thus, the converter has $p-1$ floating voltage sources. In order to ensure normal operations, it is necessary to guarantee a balanced distribution of the floating voltages for the k$^{\text{éme}}$ capacitor.

$$V_{c_k} = k\frac{E}{p} \tag{1}$$

Where k=1, …, p-1

The output voltage V_s can attend p voltage levels $\frac{E}{p},\ldots(p-1)\frac{E}{p},E$ [10].

The general state space representation of the p-cells converter is given by the system 2:

$$\begin{cases} \dfrac{dV_{c_1}}{dt} = \dfrac{1}{C_1}(u_2 - u_1)i_{ch} \\ \quad\vdots \\ \dfrac{dV_{c_{p-1}}}{dt} = \dfrac{1}{C_{p-1}}(u_p - u_{p-1})i_{ch} \\ \dfrac{di_{ch}}{dt} = -\sum\limits_{k=1}^{p}(u_{k+1} - u_k)\dfrac{V_{c_k}}{L} - \dfrac{R}{L}i_{ch} \end{cases} \tag{2}$$

Where $u_{p+1} = 0$ and $V_{c_p} = E$

For this model the load current i_{ch} and the floating voltage V_{C_k} are used as space variable such that:

$$\dot{X} = AX + B(X)U \tag{3}$$

$X = \begin{bmatrix} V_{c_1} & V_{c_2} & \cdots & V_{c_p} & i_{ch} \end{bmatrix}^T$ is the continuous state vector and $u = \begin{bmatrix} u_1 & \cdots & u_p \end{bmatrix}^T$ the applied control input.

The state matrix A is defined as follows:

$$A = \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -\dfrac{R}{L} \end{bmatrix} \tag{4}$$

and the control matrix $B(X)$ is given by the following expression :

$$B(X)=\begin{bmatrix} -\frac{i_{ch}}{C_1} & \frac{i_{ch}}{C_1} & 0 & \cdots & 0 \\ 0 & -\frac{i_{ch}}{C_2} & \frac{i_{ch}}{C_2} & \cdots & 0 \\ \cdots & 0 & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & -\frac{i_{ch}}{C_{p-1}} & \frac{i_{ch}}{C_{p-1}} \\ \frac{V_{C_1}}{L} & \frac{V_{C_2}-V_{C_1}}{L} & \cdots & \frac{V_{C_{p-1}}-V_{C_{p-2}}}{L} & \frac{E-V_{C_{p-1}}}{L} \end{bmatrix} \quad (5)$$

For the case of an open loop control, figure 6, each multi cellular converter switch is controlled by a Pulse Width Modeled (PWM) signal. The control signals have a some constant frequency shifted by $\frac{k}{p}$.

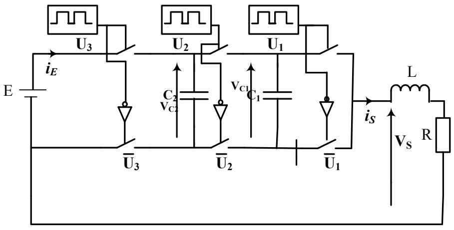


Figure 6. Multicellular converter controlled in open loop

B. Proposed closed loop control

The main objective of the proposed control law is to regulate the output current and all voltages across the flyting capacitors at the desired values.

Before the application of the proposed control law, we propose to apply a feedback linearization technique to facilitate the control law synthesis [5].

In order to linearize the mathematical system (2) we define the control input u as follows:

$$u=-FX+Le \quad (6)$$

Thus, the state space representation is transformed into the following equation:

$$\dot{X}=\left(A-BF\right)X+BLe \quad (7)$$

$$\dot{X}=A_dX+B_de \quad (8)$$

Let us consider Ad and Bd respectively as the desired state space and control matrix defined as follows:

$$A_d=\left(A-BF\right) \quad (9)$$

and

$$B_d=BL \quad (10)$$

Let us assume that Ad and Bd has the following linear forms:

$$A_d=\begin{bmatrix} \frac{E}{C_1} & 0 & \cdots & 0 \\ 0 & \frac{E}{C_2} & \cdots & \vdots \\ 0 & 0 & \ddots & 0 \\ 0 & \cdots & 0 & -\frac{R}{L} \end{bmatrix} \quad (11)$$

$$B_d=\begin{bmatrix} -\frac{E}{C_1} & 0 & \cdots & 0 \\ 0 & -\frac{E}{C_2} & \cdots & \vdots \\ 0 & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \frac{R}{L} \end{bmatrix} \quad (12)$$

The matrix F and L matrix are defined as follows:

$$F=B^{-1}\left(A-A_d\right) \quad (13)$$

$$L=B^{-1}B_d \quad (14)$$

To apply the feedback linearization described approach, the matrix B must be inversible. Indeed, we demonstrated in the paper that:

$$\det B(X)=\frac{i_{ch}^{n-1}}{C_1C_2\dots C_{n-1}}\frac{E}{L} \quad (15)$$

As the controlled system is linear it is easy to deduce the IP control parameters. The bloc diagram of the proposed control is shown in figure 7.

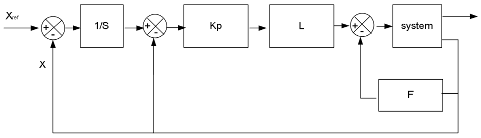


Figure 7. Proposed IP control

IV. SIMULATION RESULTS

For the validation of the proposed feedback linearization, we consider 3-cells converter connected to an RL load, figure 8.

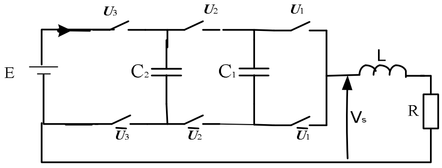


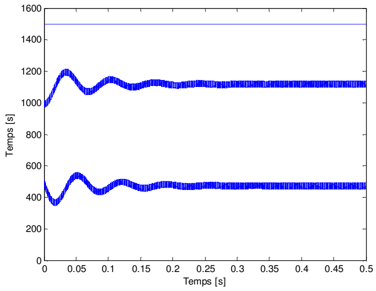
Figure 8. Studied three-cell converter.

The parameters of the studied converter are given in Table1.

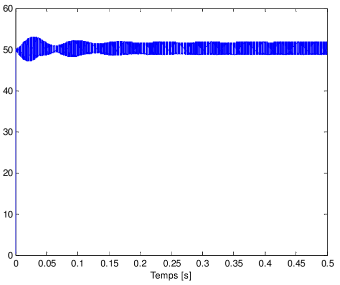
TABLE 1. STUDIED MULTI CELLULAR CONVERTER PARAMETERS

Components	**Rating values**
E	1500V
L	1mH
C_1, C_2	40µF
R	10Ω

Figure 9 gives the simulation results for the 3 cells converter controlled in open loop. Figure9.a shows the evolutions of the floating voltages V_{C_1} , V_{C_2} and E and the figure 9.b presents the load current evolution.



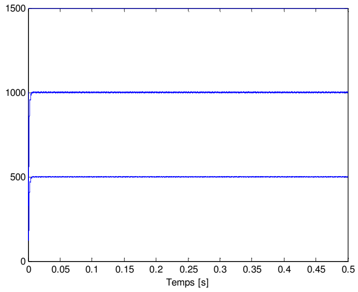
a- floating voltages evolution



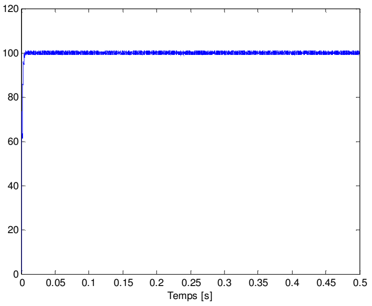
b- load current evolution

Figure 9. Simulation results for current and voltages in open loop

Figure 10 presents the simulation results obtained by application of the IP control. Thus, figure 10.a and 10.b present respectively the floatting voltages and the load current evolution. Figure 10.a presents the load current and the floating voltage for a desired current I_{ref}=100A. The application of the closed loop control law allows the reduction of the current ripple and voltage.



a- Floating voltages V_{C_1} , V_{C_2} and E evolutions



b- load current i_{ch} evolution

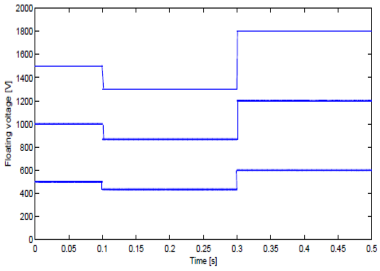
Figure 10. Simulation results for current and voltages with IP regulator

To test the robustness of the proposed IP control, we consider the variation of the input voltage and the load resistor.

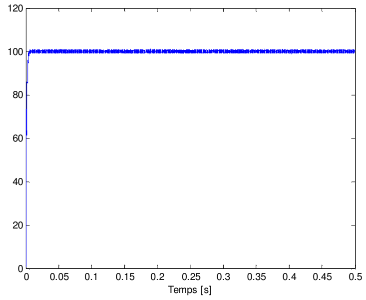
For the case of an input variation according to the following sequences:

- t=0ms start input voltage with E=1500 V;
- t=10ms E=1300 V ;
- t=30ms E=1800 V ;

The obtained simulation results are given in figures 11.a and 11.b.



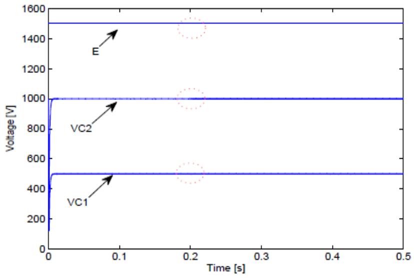
a-Floating voltages V_{C_1} , V_{C_2} and E evolutions



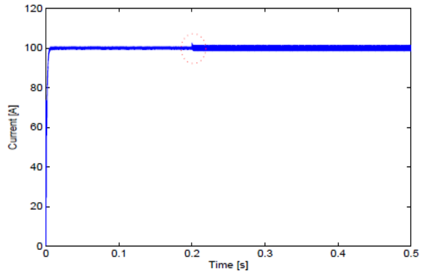
b- Load current i_{ch} evolution

Figure 11. Simulation results for current and voltages with IP regulator of an input variation

For the case of load variation occurring at t=20ms, when the resistor load became the twice of its value. The simulation results are given in figures 12a and12.b.



a- Floating voltages V_{C_1} , V_{C_2} and E evolutions



b- Load current i_{ch} evolution

Figure 12. Simulation results for current and voltages with IP regulator for load variation

Thus, the proposed control low is suitable for the studied converter.

Moreover, it rejects external perturbations and some controlled system parameter variations.

From this test we can confirm that the proposed control is robust for the considered load variation.

V. PROPOSED HIL SIMULATION PROCEDURE

The proposed IP control was tested by application of HIL simulation. The simulation platform is organized as shown in the figure 13. The control law was programmed using Labview graphical programming language. It was implemented in a compact RIO (cRIO) which is an industrial controller incorporating a FPGA and a real time processor.

The plant, which is in our application a multicellular converter, was modeled by using simulink software. The simulated model was compiled to generate a dll for National Instrument Veristand software which allows real time tests. So as a first approach, the model can be simulated in the computer. So data acquisition cards are needed o link the real time controller (cRIO) and the computer. The control signal generated from the controller is a analog voltage which is transformed by the simulation model into 3 PWM control signal for the converter switch. It is, also, possible also to generate PWM control signal to be applied directly to the simulated converter.

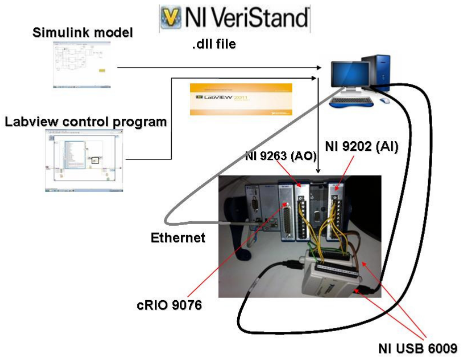


Figure 13. HIL simulation platform

The simulated signals are presented in figure 14. With veristand software it is possible to visualize all the simulated inputs and outputs and also the data acquisition cards inputs outputs. So, Figure 14 and 15 are respectively two zooms of the PWM control signal for switch U_3 and the output voltage.

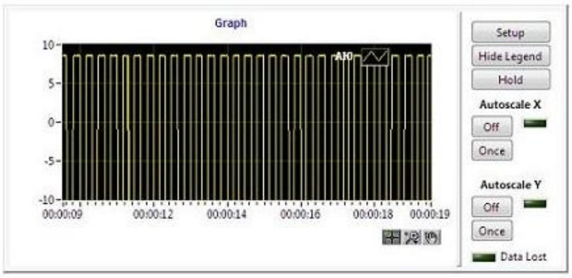


Figure 14. HIL simulated generated PWM control signal by application of the IP control

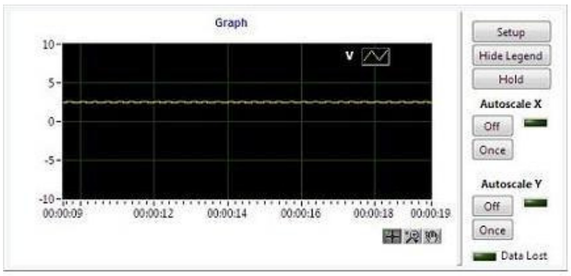


Figure 15. Simulated HIL output voltage by application of the IP control

VI. CONCLUSION

In this paper, a closed loop control law based on a IP regulator have been designed for a multi cellular converter. In order to validate the proposed control law after simulation tests, we proposed HIL simulation. Indeed, it is risky to perform tests directly because multi cellular converter is used for very high power applications. For the proposed HIL simulation approach we used a real time controller incorporating FPGA and a processor and some HIL dedicated software. Thus, the proposed control law was validated and tested with success by application of the proposed HIL simulation approach.

REFERENCES

[1] NASA Systems Engineering Handbook, NASA Center for AeroSpace Information, (2002).

[2] S.Raman, N. Sivashankar, W. Milam, W. Stuart, and S. Nabi, "Design and Implementation of HIL Simulators for Powertrain Control System Software Development", Proceedings of the American Control Conference,(1999).

[3] Al-Hammouri, A.T; Nordstrom, L.; Chenine, M.; Vanfretti, L.; Honeth, N.; Leelaruji, R. "Virtualization of synchronized phasor measurement units within real-time simulators for smart grid application". Power and Energy Society General Meeting, 2012 IEEE: 1–7, (2012).

[4] A. Palladino, G. Fiengo, F. Giovagnini, and D. Lanzo, "A Micro Hardware-In-the-Loop Test System", IEEE European Control Conference, (2009).

[5] Ben Said, S., Ben Saad, K., and Benrejeb, M., "SLIDING MODE CONTROL FOR A MULTICELL CONVERTERS", International Conference on Control, Engineering et Information Technology, vol. 1, June (2013).

[6] Sadigh, A.K., Hosseini, S.H., and G.B. Gharehpetian, "Double flying capacitor multicell converter based on modified phase-shifted pulsewidth modulation", IEEE Transactions on Power Electronics, vol. 259, no. 6, pp. 1517-1526, June (2010).

[7] M. Ghanes,F. Bejarano and J.P. Barbot, "On sliding mode and adaptive observers design for multicell converter" Proceedings of the 2009 IEEE ACC, pp. 2134-2139, June (2009).

[8] A.M. Lienhardt, G. Gateau and T. Meynard, "Digital sliding-mode observer implmentation using FPGA", IEEE Trans. Industrial Electronics, vol. 54, n°4, pp. 1865-1875, August (2007).

[9] R. Stala, S. Pirog, A. Mondzik, M. Baszynski, A. Penczek, J. Czekonski and S. Gasiorek, "Results of investigation of multicell converters with balancing circuit," IEEE Trans. Industrial Electronics, vol. 56, no. 7, pp. 2620--2628, July(2009).

[10] D. Patino, P. Riedinger and C. Iung, "Predictive control approach for multicellular converters," Proceedings of the 2008 IEEE IECON, pp. 3309-3314, November (2008).

[11] T.A. Meynard, H. Foch, P. Thomas, J. Courault, R. Jakob and M. Nahrstaedt, "Multicell converters: basic concepts and industry applications," IEEE Trans. Industrial Electronics, vol. 49, no. 5, pp. 955-964, October(2002).

[12] G. Gateau, M. Fadel, P. Maussion, R. Bensaid and T.A. Meynard, "Multicell converters: active control and observation of flying-Capacitor voltages," IEEE Trans. Industrial Electronics, vol. 49, no. 5, pp. 998--1008, October (2002).

[13] Ghanes M., Barbot J. P., "On sliding mode and adaptive observers design for multicell converter", IEEE American Control Conference, St Louis, Missouri, USA, (2009).

[14] R.H. Wilkinson, T.A. Meynard and H. du Toit Mouton, "Natural balance of multicell converters: The two-cell case," IEEE Trans. Power Electronics,} vol. 21, no. 6, pp. 1649-1657, November (2006).