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NON LINEAR CONTROL STRATEGY FOR POWER FLOW BETWEEN TWO DC GRIDS

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***Abstract*— This paper presents a detailed control strategy to a PWM bidirectional DC-DC transferring system designed for high voltage, high power applications. The objective is to realize precise bidirectional power flow control between two DC grids, where the half bridge topology is adopted for the connection between them. By using the averaging technique, the system's nonlinear average model is derived, based on which the nonlinear control algorithm is proposed, to realize the current control. The proposed circuit and control strategies are simulated using Sim Power Systems and a comprehensive synthesis of the control algorithms is conducted, from the viewpoint of rapidity, robustness and system cost. It is verified that the proposed nonlinear control algorithm has a fast response, competent disturbance rejection ability and low cost. Although the structure studied here is the half bridge bidirectional converter, however, the controller design methods and the relative conclusions can be promoted to any type of structure in power transferring systems.**

Keywords-half bridge converter; power flow control; nonlinear control; Lyapunov function

I. INTRODUCTION

Power flow control between two DC grids is an area that has seldom been touched before. The objective of constructing such a system is to realize the bidirectional power flow control between two DC grids. In order to connect the two DC grids with different voltage levels, a DC-DC converter is indispensable for utilization. The bidirectional half bridge converter is proved to be an effective solution for high voltage-high power conditions, as fewer semiconductor devices are utilized. Moreover, for the purpose of eliminating the high frequency current fluctuations caused by the switch's commutation, two current filters are added to ensure that the currents debited by the two DC grids are little-rippled. However, the introduction of two current filters also increases the order of the system, thus increases the control complexity.

There exist many strategies for stabilizing and regulating DC/DC converter's output. The objective of controlling such proposed systems is to provide better performances, ensure closed loop stability and guarantee the adequate behaviour. In terms of converter controller design, the use of averaging techniques leads to the establishment of a nonlinear mathematical model. Moreover, in our proposed system, the added input and output current filter makes it a 5-order system which signifies that a simple linear PI or PID controller is very cumbersome for regulation. Under this circumstance, other researchers try to explore the non-linear characteristics of the dc/dc converters and proposed several relative control algorithms, but the proposed methods are too difficult to be comprehended and realized in industrial utilization. The control algorithm proposed in this paper is totally based on the system's nonlinear characteristics and is comparably easy to realize. The synthesis of the power transferring system and the associated control strategy will be discussed in detail in the following parts.

II. SYSTEM MODELLING

Supposing that the power transferring system studied here realizes the bidirectional power flow between two DC grids, 150kV for Port A and 30kV for Port B, separately. The system consists of a half bridge bidirectional converter and two current filters, as shown in the figure 1.

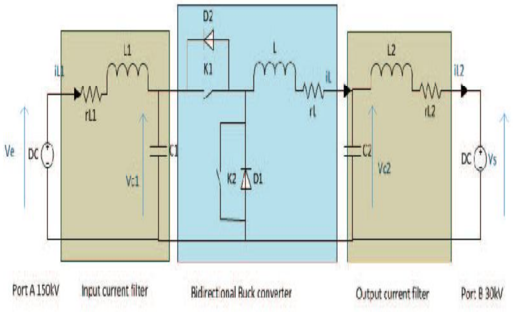


Figure 1. The studied power transferring system

The switch K_1, the diode D_1 and the inductance L form a standard buck converter. Adding an anti-parallel diode D_2 and a controllable switch K_2 makes the circuit possible to operate in two directions. To realize the bidirectional power flow, the switch K_1 and K_2 are controlled by PWM signal in the complementary way. In order to eliminate the current fluctuations caused by the circuit switching, a current filter composed by L_1 and C_1 is placed at the side A and another current filter composed by L_2 and C_2 is placed at the side B. The resistance r_{L1}, r_{L2} and r_{L2} are the series resistance of the inductance L_1, L and L_2, respectively.

Thus before system modeling, these following hypotheses are important:

(1) Neglecting the switch's and diode's forward voltage.

(2) Considering the switch's and diode's on resistance, neglecting its parasite capacity.

(3) Considering the inductance series resistance r_{L1}, r_{L2} and r_{L2}, respectively, for the three inductors.

Supposing that the circuit operates in the continuous conduction mode (CCM) and the power transferring direction is from the port A to the port B (down mode). In this mode, there are apparently two operational configurations, which depend on the position of K_1. When K_1 is switched on, it is defined as the configuration A; when K_1 is switched off, it is defined as the configuration B.

A. *Down mode, Configuration A*

Between the phase [o,dT], K1 is switched ON, the diode D1 is reverse-biased, the system's equivalent circuit is shown in the following figure.

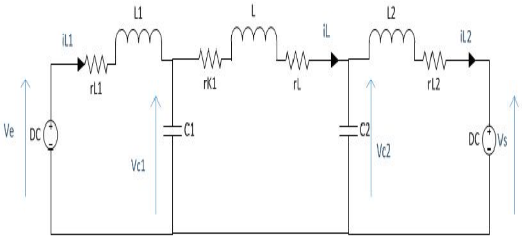


Figure 2. The Equivalent circuit of the configuration A in down mode

Selecting the inductor's currents and capacitor's voltages as the state variables, $x=[x1\ x2\ x3\ x4\ x5]^T = [iL1\ vC1\ iL\ vC2\ iL2]^T$, the following equation can obtained.

$$\left.\begin{aligned} v_e &= i_{L1} r_{L1} + L1 \frac{di_{L1}}{dt} + v_{c1} \\ i_{L1} &= C1 \frac{dv_{C1}}{dt} + i_L \\ v_{c1} &= (r_{k1} + r_L) i_L + L \frac{di_L}{dt} + v_{c2} \\ i_L &= C2 \frac{dv_{C2}}{dt} + i_{L2} \\ v_{C2} &= v_s + r_{L2} i_{L2} + L2 \frac{di_{L2}}{dt} \end{aligned}\right\} \qquad (1)$$

Therefore, the state space model at the interval [0 *d*T] can be described by the following equation (the objective is to regulate the output current i_{L2} thus it is considered as the output in the state space model):

$$\begin{aligned} \dot{x} &= A_1 x + B_1 v_e + C_1 v_s \\ y = i_{L2} &= E_1 x \end{aligned} \qquad (2)$$

B. Down mode, Configuration B

Then at the phase [*d*T, T], K1 is switched off, D1 is forward- biased, thus the system equivalent circuit can be shown in the Figure 3.

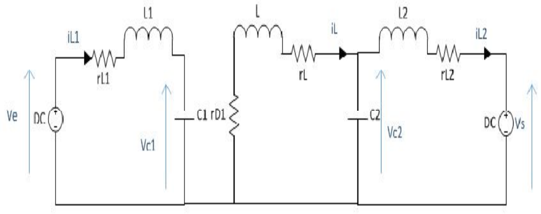


Figure 3. The Equivalent circuit of the configuration B in down mode

Similarly, the following equations can be obtained.

$$\left\{\begin{aligned} v_e &= i_{L1} r_{L1} + L1 \frac{d_{L1}}{dt} + v_{C1} \\ i_{L1} &= C1 \frac{dv_{c1}}{dt} \\ 0 &= (r_{D1} + r_L) i_L + L \frac{d_{iL}}{dt} + v_{C2} \\ i_L &= C2 \frac{dv_{C2}}{dt} + i_{L2} \\ v_{C2} &= v_S + r_{L2} i_{L2} + L2 \frac{di_{L2}}{dt} \end{aligned}\right. \qquad (3)$$

$$\left\{\begin{aligned} \dot{x} &= A_2 x + B_2 v_e + C_2 v_S \\ y &= i_{L2} = E_2 x \end{aligned}\right. \qquad (4)$$

The conventional way for modeling power converters is to take an average value of the system state over a switching cycle. In order to obtain this model, we consider that the converter dwells between its two configurations, thus the system's state space average model can be expressed by grouping the two state space equations using the duty cycle d.

III. CONTROL ALGORITHM

A nonlinear control algorithm that fully adapted to the system's nonlinearities characteristics is proposed to regulate the system's output, for the purpose of providing more alternatives and comparing the performances of the two control strategies.

For the state space average, the model is reassembled to separate the linear and nonlinear part. The equation can be written in the following form:

$$\dot{X}_2 = \begin{bmatrix} 0 & -\frac{1}{C2} \\ \frac{1}{L2} & -\frac{r_{L2}}{L2} \end{bmatrix} \begin{bmatrix} x4 \\ x5 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{L2} \end{bmatrix} v_S + \begin{bmatrix} \frac{x3}{C2} \\ 0 \end{bmatrix} \qquad (5)$$

Where

$$X_1 = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \quad X_2 = \begin{bmatrix} x_4 \\ x_5 \end{bmatrix} \qquad (6)$$

In the equation (5) and (6), we use the simplified form x to represent the state space average vector <x>, for the purpose of briefly illustrating the system and the control strategy. But the x used in this part also signifies the averaged vector obtained in a switching cycle.

The nonlinear regulator is designed step by step, which means that we begin from the sub-equation which contains the reference signal and try to find out the variation of the other variable. The controller is obtained directly from the state space nonlinear average model, which contains some nonlinear parameters. It has been presented a nonlinear adaptive controller for the regulation and synchronization of interleaved buck converters and has obtained good transient response and closed loop stability. But the described controller can not fully adapt to our proposed system. A new nonlinear control algorithm will be explored specially for the power transferring systems descried.

1)Take firstly the last sub-equation of the equation (7) into consideration, as shown in the equation(8).

$$\dot{x}_5 = \frac{1}{L_2}x_4 - \frac{r_{L2}}{L_2}x_5 - \frac{1}{L_2}v_s \qquad (7)$$

The objective of system's regulation in this part is to find a control algorithm that permits to get the variation of x4 for regulating x5 to x5ref (iL2ref). With the help of Lyapunov function, which is shown in the equation (7), it is possible to design such a regulator.

$$V_{x5} = \frac{1}{2}(x_5 - x_{5ref})^2 \qquad (8)$$

Achieving the tracking objective mean forcing the error to vanish. To ensure the stability, it has to maintain that the:

$$\dot{V}_{x5} \le 0 \qquad (9)$$

Supposing that:

$$\frac{1}{L_2}x_4 - \frac{r_{L2}}{L_2}x_5 - \frac{1}{L_2}v_s - \dot{x}_{5ref} = -\alpha_{x5}E_{x5} - \beta_{x5}\mathrm{sign}(E_{x5})$$

With parameters $\alpha_{x5} > 0$, $\beta_{x5} > 0$.

$$x_4 = x_{4ref} = L_2\left[\frac{r_{L2}}{L_2}x_5 + \frac{1}{L_2}v_s + \dot{x}_{5ref} - \alpha_{x5}E_{x5} - \beta_{x5}sign(E_{x5})\right] \qquad (10)$$

Thus, theoretically, the equation (10) is developed for the regulation the sub-system to get the x_{4ref} for a given desired x_{5ref}. The sufficient condition for assuring the stability is to assure $\alpha_{x5} > 0$ and $\beta_{x5} > 0$. In fact, regulating the coefficient α_{x5} permits to ameliorate the response time and regulating the coefficient β_{x5} permits to assure the robustness of the closed loop system.

IV . SIMULATIONS AND RESULTS

The modelling system is shown in the figure 5, which can be divided into 3 parts: the main system, the measurement and the control part. The main system is a classical half bridge bidirectional converter, which is realized by adding a diode with the IGBT or adding an IGBT with the diode. The two IGBTs are commanded in the complementary way thus a logical operator "NOT" is used for the switching of the second IGBT K2.

This configuration guarantees the bidirectional current flow of the system between the BC grid 150kV and the DC grid 30kV. The simulation front panel is shown in the following figure.

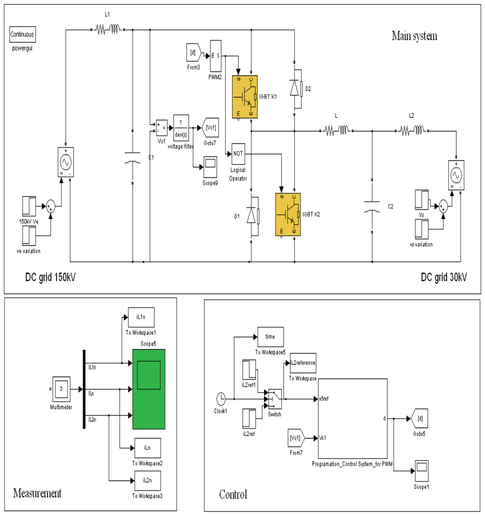


Figure 5. The simulation front panel using the proposed nonlinear algorithm

The simulation configurations are prescribed as follows: At the time t=0.1s, a command of i_{ref} =50A is imposed. The output voltage is shown in the following figure.

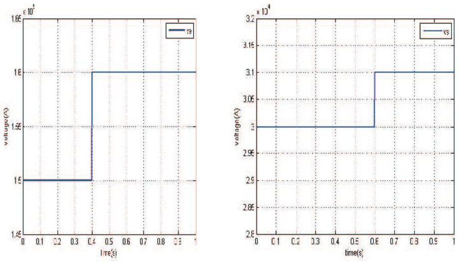
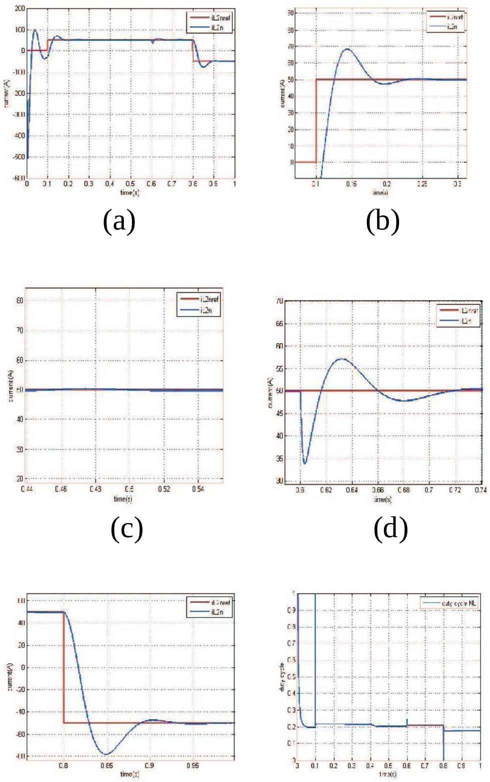

(a) (b)

Figure 6. The Perturbations of input and output voltages of the DC power system

Otherwise, the system should also be able to operate in the other power transferring direction, thus at t=0.8s, a command of i_{ref} = -50A is added. In this condition, the power flow direction should be: from the DC grid 30kV to the DC grid 150kV. The simulation results and the zooms at several instants for the current i_{L2} are shown below.


(a) (b)

(c) (d)

(e) (f)

Figure 7. (a)-(e): Current responses of i_{L2} under nonlinear control, and the zoom at t=0.1s 0.4s, 0.6s and 0.8s. (f) The relative variation of duty cycle.

The current response i_{L2} is a very important indicator of the power received or debited by the Port B (DC grid 30kV), at down mode or up mode, separately. As shown in the figure 7(b), the current response to the reference signal is very fast (response time of 0.4s), with an overshot of 34%. In the figure 7(c), the perturbation Δv_e causes nearly negligible influences to the system's output, which confirms the robustness of the proposed nonlinear controller. The figure 7(f) verifies that the variation of the duty cycle under nonlinear control strategy is limited to [0, 1]. The variation of the duty cycle at different stages shows clearly the power flow conditions.

CONCLUSIONS

This paper presents a nonlinear control algorithm for regulating the power flow between two DC grids. The proposed nonlinear control algorithm is a new approach for controlling the DC-DC bidirectional power transferring system, based on the exploration of system's nonlinearities and Lyapunov function. The system is modeled in the environment Simulink by using SimPowerSystems and the simulation results obtained for the proposed control algorithms are illustrated and explained.

As to the aspect of system robustness, the nonlinear controller's performance is also competent, especially to the perturbation of the input voltage where nearly no influence at the transferring current is provoked. Moreover, it is simple to be realized by DSP programming. In conclusion, the proposed nonlinear control exploits the nonlinearity and time-varying properties of the system.

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