

Fuzzy Control of a Bi-directional Inverter with Nonlinear Inductance for DC Microgrids

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Abstract—This paper proposes the design of fuzzy control of a bi-directional converter with variable inductance for dc microgrids. The nonlinear inductance model is developed and taken into consideration in the controller design of the bi-directional inverter to promote the performance. A novel fuzzy control strategy is proposed to increase the magnetizing voltage such that the current distortion is reduced. Simulated results demonstrated the effectiveness of the design.

Keywords- Bi-directional converter, fuzzy control, dc microgrids

I. INTRODUCTION

Energy crisis inevitably brings nearer for the depletion of fossil. The greenhouse effect becomes more serious by the increased requirements for electric power. In recent years, renewable energy has received great attention due to the advantages of clean, no pollution and huge reserves. Many distributed generations such as photovoltaic cells, wind turbines and fuel cells have been linked with the utility grids [1]. However, the power quality of utility grids will be decreased by distributed generations [2]. To reduce conversion losses and supply high quality power, the dc microgrid is proposed in this paper.

Power electronic converters are one of the most important devices among the components of the microgrid [3]. In this paper, a bi-directional converter is designed to regulate the dc bus voltage for different types of energy sources and energy storage. The functions of the bi-directional inverter include grid connection mode and rectification mode. Fig. 1 shows the schema of the microgrid system.

The inductance is usually assumed to be a constant in the design of the inverter controller [4]. However, the inductance is a highly nonlinear function varied with the current. It is important to take the inductance variation into account when the operational principle of the bi-directional inverter is designed. In this paper, the methodology of nonlinear least squares is applied to build the nonlinear inductance model such that the performance of the bi-directional inverter is improved. Besides, the magnetizing voltage will be too low to track the reference current if the inductor is magnetized only with line voltage in rectification mode. A current hollow will appear near the zone of zero crossing no matter how the control duty ratio is filled. Thus, a novel fuzzy control strategy is proposed to

increase the magnetizing voltage such that the current distortion is reduced.

Fuzzy theory is introduced by Zadeh in 1965 [5]. In artificial intelligence, fuzzy sets could be applied to control the plant. Based on fuzzy logic, a fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge. The main feature [6] of fuzzy control is that the controller design doesn't rely on a mathematical model of a plant. The fuzzy inference system employing fuzzy if-then rules can control a plant using the human knowledge. Fuzzy controller has been widely used in industry for its easy realization and good robustness. Accordingly, the fuzzy logic is employed to design the PWM gain of the bi-directional inverter for dc microgrid.

The rest of this paper is organized as follows. Section 2 describes the model of the bi-directional inverter. Section 3 proposes the design of fuzzy controller. Section 4 shows simulation results with the presented scheme. Section 5 gives the conclusion.

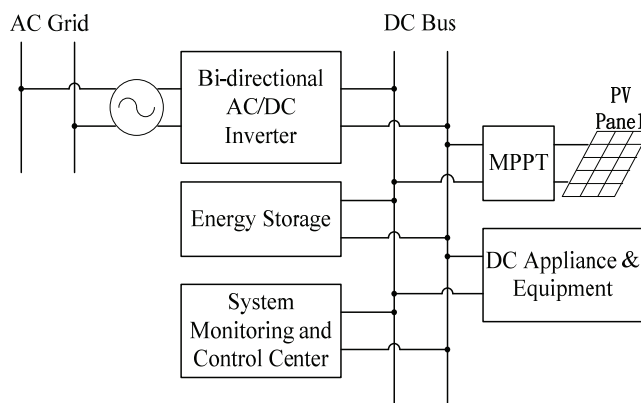


Fig. 1 The schema of the microgrid system

II. THE BI-DIRECTIONAL INVERTER

A. Circuit Configuration

Fig. 2 shows the proposed bi-directional inverter with a full-bridge configuration. The functions of the bi-directional

inverter include grid connection mode and rectification mode. The inverter senses inductor current i_L and uses the dc-link voltage v_{dc} and line voltage v_s in the single-chip microcontroller (dsPIC30F2023) to determine a control for operating the inverter stably.

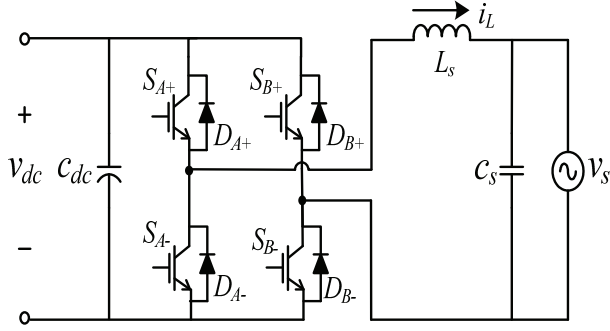


Fig. 2 The circuit configuration of the bi-directional inverter

B. Duty Ratio

In the grid connection mode, $\Delta i_L = \Delta i_{L(on)} + \Delta i_{L(off)}$

$$\Delta i_L = \frac{v_{dc} - |v_s|}{L} d T_s - \frac{|v_s|}{L} (1-d) T_s \quad (1)$$

where T_s is the period of the PWM. The duty ratio can be expressed as

$$d = \frac{\Delta i_L \cdot L}{v_{dc} \cdot T_s} + \frac{|v_s|}{v_{dc}} \quad (2)$$

In the rectification mode,

$$\Delta i_L = \frac{|v_s|}{L_s} d T_s - \frac{v_{dc} - |v_s|}{L_s} (1-d) T_s \quad (3)$$

The duty ratio can be expressed as

$$d = \frac{\Delta i_L \cdot L_s}{v_{dc} \cdot T_s} + \frac{v_{dc} - |v_s|}{v_{dc}} \quad (4)$$

C. Nonlinear Inductance Model

Let the nonlinear inductance model be

$$y = f(x) = ax^2 + bx + c \quad (5)$$

where y is the estimated value of inductance, x is the value of current. The sum of square error between the estimated and measured value of inductance will be

$$\sum [ax_i^2 + bx_i + c - y_i]^2 \quad (6)$$

where n is the total number of experimental data (x_i, y_i) .

To minimize the sum of square error, taking the partial derivative to a , b and c , respectively gets

$$\begin{cases} \sum 2x_i^2(ax_i^2 + bx_i + c - y_i) = 0 \\ \sum 2x_i(ax_i^2 + bx_i + c - y_i) = 0 \\ \sum 2(ax_i^2 + bx_i + c - y_i) = 0 \end{cases} \quad (7)$$

After substituting the experimental data (x_i, y_i) into the above equation, we can get a nonlinear inductance model to approximate the nonlinear mapping between the inductance and the current.

D. Refining Tracking Error

If the inductor L_s is magnetized by only turning on S_{A+} in the rectification mode, the magnetizing voltage v_s will be too low to track the reference current near the zero crossing. To refine the waveform of inductor current, a novel PWM strategy is developed as shown in Fig. 3. The magnetizing voltage should be increased to $v_L = v_{dc} + v_s$ by appropriately turning on S_{A+} and S_{B-} .

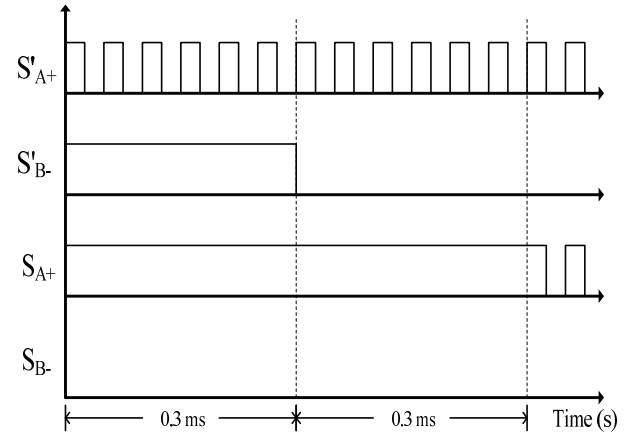


Fig. 3 Different switching sequence

III. FUZZY CONTROL

A. Fuzzification

The design procedure of fuzzy logic controller includes fuzzification, fuzzy rule base, fuzzy inference and defuzzification. In this paper, the linguistic variables are state error e , change in error Δe and fuzzy gain u . The Mamdani fuzzy inference system uses minimum and maximum for T-norm and T-conorm operators, respectively.

The fuzzy sets and the fuzzy rules are defined as follows. The linguistic variables of input e and Δe are defined as {N, Z, P}, where N means negative, Z means zero and P means positive. The linguistic variables of output u are defined as {SS, SM, SB, MS, MM, MB, BS, BM, BB}, where S means small, M means medium and B means big.

The universe of discourse of e is assigned to be [-1 1]. The universe of discourse of Δe is assigned to be [-1 1]. The membership functions of the fuzzy sets corresponding to variables e and Δe are shown in Fig. 4.

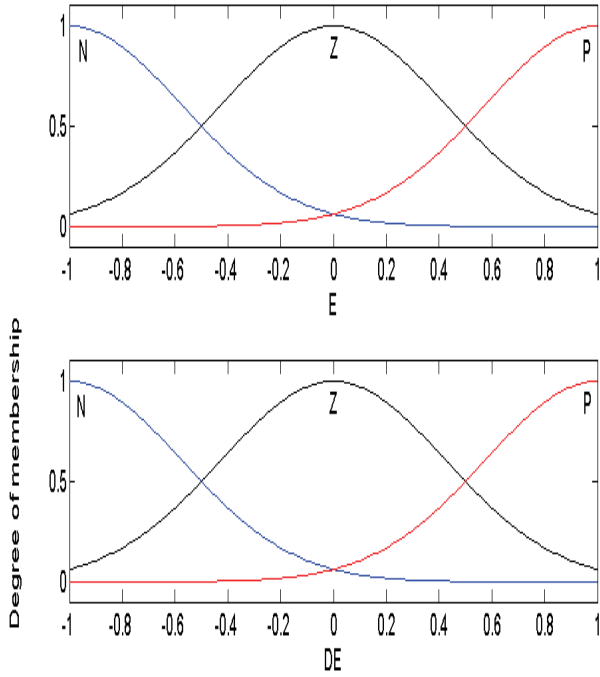


Fig. 4 Membership Functions

B. Fuzzy Inference Engine

The minimum inference engine is applied to design fuzzy inference mechanism in this study. With max-min composition, the consequence $\mu_{B'}(y)$ is

$$\mu_{B'}(y) = \max_{l=1}^m [\mu_{A_1^l}(x_1) \wedge \mu_{A_2^l}(x_2) \wedge \mu_{B^l}(y)] \quad (8)$$

where x_1 , x_2 and y represent the fuzzy sets e , Δe and u , respectively; $\mu_{A_1^l}(x_1)$, $\mu_{A_2^l}(x_2)$ and $\mu_{B^l}(y)$ mean the membership functions of e , Δe and u , respectively; l is the index of membership functions for every fuzzy set; m is the number of triggered fuzzy rules.

C. Fuzzy Rules

According to the Mamdani inference method, fuzzy if-then rules are designed. By means of using three linguistic variables N, Z and P of each input variable, nine fuzzy rules are derived. These fuzzy inference rules are summarized in Table 1.

Table 1. Fuzzy inference rules

		$e(t)$			
			N	Z	P
Δe	N		BM	SM	MM
	Z		BS	SS	MB
	P		MS	SB	BB

D. Defuzzification

Defuzzification is used to extract a crisp value from a fuzzy set. There are a lot of methods for defuzzifying a fuzzy set. The center of gravity defuzzification is used in this paper

$$Y^* = \frac{\sum_{i=1}^m \mu_{B^i}(y_i) \cdot y_i}{\sum_{i=1}^m \mu_{B^i}(y_i)} \quad (9)$$

where Y^* is the crisp values of fuzzy gain u , i is the index of consequent rules.

IV. SIMULATION RESULTS

Fig. 5(a) shows the experimental data of measured inductance. After substituting these experimental data (x_i , y_i) into the equation (7), we can get the following nonlinear inductance model

$$L_S = 2.851I_L^2 - 244.6I_L + 5604 \quad (10)$$

Fig. 5(b) shows the comparison between the nonlinear inductance model and the measured values. Obviously, the nonlinear model is very similar to the experimental data.

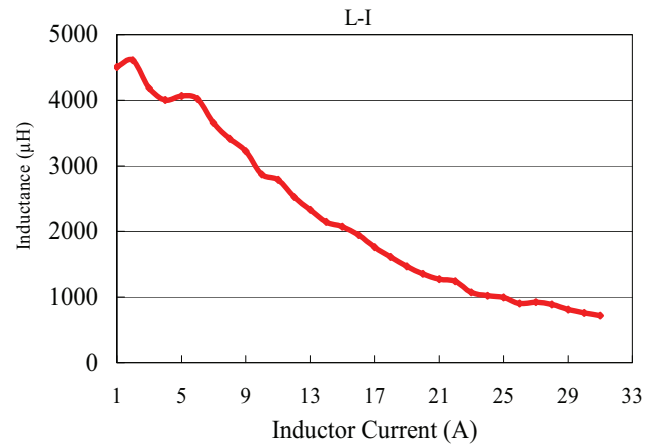


Fig. 5(a) Experimental data of inductance variation

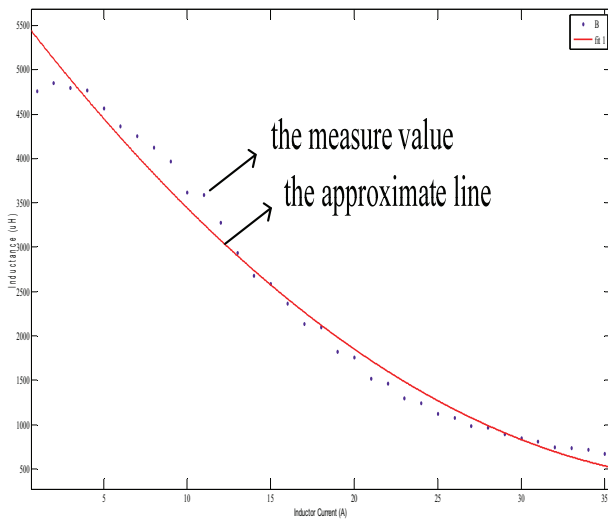


Fig. 5(b) The nonlinear model of inductance variation

Modeling and simulation are essential for developing controller programs. In this paper, the Matlab and Simulink software is utilized for modeling and simulating. Fig. 6(a) shows the simulation response without considering inductance variation in the grid connected mode. Fig. 6(b) shows the simulation response considering inductance variation in the grid connected mode. Apparently, the inductance current will have better waveform when the controller design takes the inductance variation into consideration. Fig. 7(a) shows the simulation response without considering inductance variation in the rectification mode. Fig. 7(b) shows the simulation response considering inductance variation in the rectification mode. Again, the inductance current will have more fluctuation if the controller design shorts of inductance variation consideration. Fig. 8(a) shows the simulation response of inductor current by turning on S_{A+} only. Fig. 8(b) shows the simulation response of inductor current by turning on S_{A+} and S_{B-} . The tracking error is significantly reduced between the reference current and the inductor current.

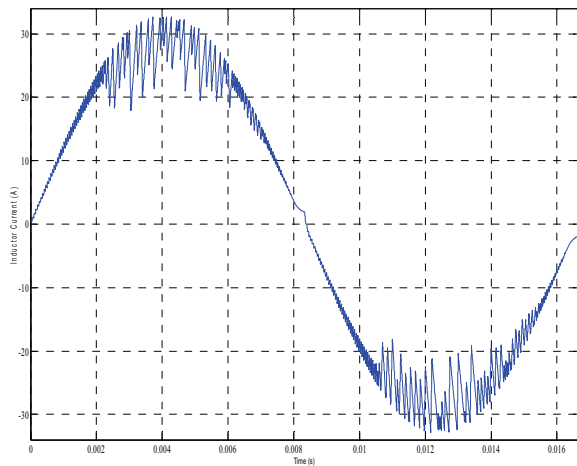


Fig. 6(a) Simulation response (GC mode) without inductance variation

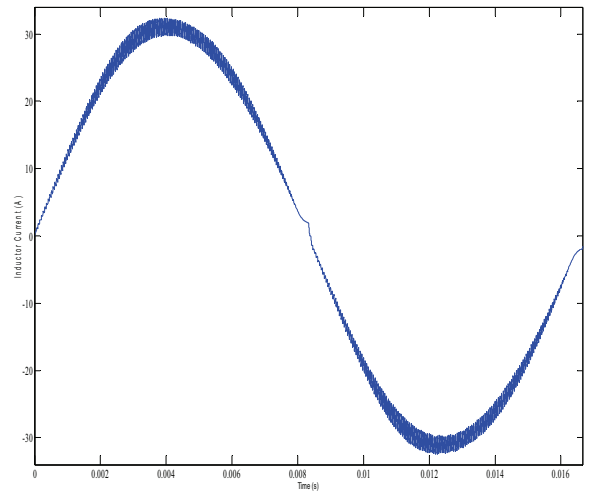


Fig. 6(b) Simulation response (GC mode) with inductance variation

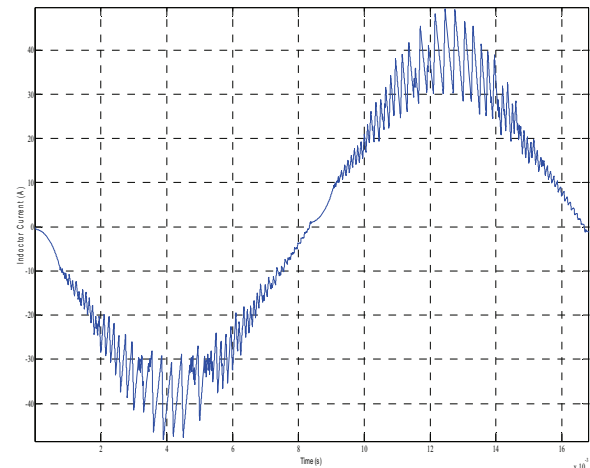


Fig. 7(a) Rectification mode without inductance variation

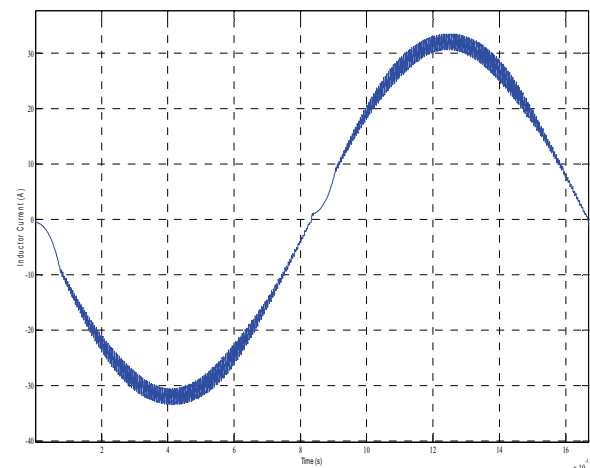


Fig. 7(b) Rectification mode with inductance variation

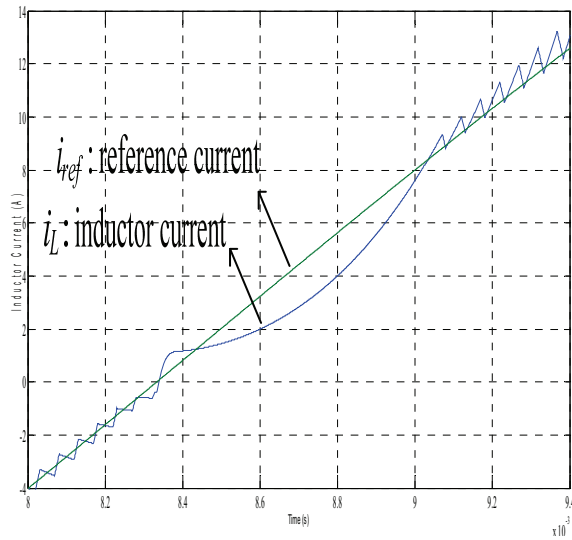


Fig. 8(a) Simulation response (S_{A+} on)

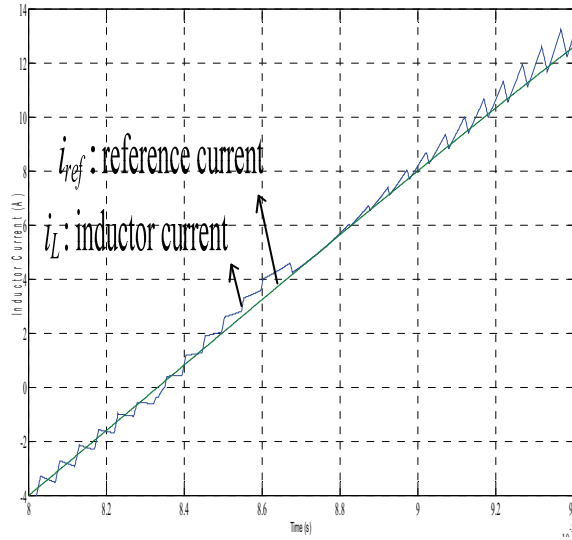


Fig. 8(b) Simulation response (S_{A+} and S_{B-} on)

V. CONCLUSION

We considered the dc bus voltage regulation problem of the bi-directional converter using fuzzy control strategy. Furthermore, to promote the regulation performance, a nonlinear inductance model between the current and the inductance mapping is established. Then, a novel fuzzy control strategy which takes account of inductance variation is proposed to increase the magnetizing voltage such that the current distortion is reduced. Last, the computer simulation shows that the fuzzy controller with inductance variation design is superior to the fuzzy controller without inductance variation design.

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