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Model Predictive Current Control with a Fixed Switching Frequency for Power Factor Corrected Rectifiers in Microgrid

Y M Hong¹, Q B Lin^{1, 2, 4}, Y Zong², Y Shi², X J Su³

¹ College of Electrical Engineering and Automation, Fuzhou University, Fuzhou 350100, Fujian, China

² The Center for Electric Power and Energy, Technical University of Denmark, Kongens Lyngby 2800, Denmark

³ Kehua Hengsheng Co., Ltd. Xiamen, 361006, Fujian, China

E-mail: qiongbnlin@fzu.edu.cn

Abstract. In this paper, a model predictive current control (MPCC) strategy with a fixed switching frequency to control the dual boost bridgeless power factor corrected (PFC) converter is proposed. The improved MPCC strategy solves the problem of filter design and the high electromagnetic interference (EMI) which caused by the traditional MPCC. With the consideration of a nonlinear inductor, a formula is fitted to represent the change of the inductance, and the improved strategy has strong robustness. The simulation and experiment shows that the quality of current and power factor of the system is improved by the proposed control strategy.

1. Introduction

With the development of renewable energy, many distributed energy sources such as Photovoltaic power system, fuel cells, etc. are used in the microgrid, which are connected to the microgrid network via electronic converters [1-2]. There are a lot of harmonic pollution due to the large use of electronic converters. Therefore, the dual boost bridgeless PFC converter is widely used in microgrid to solve the problem, which can ensure that the current quality of the equipment does not affected by the harmonics in the power grid. In this way, some precision equipment can work well, and the power factor increases, which reduces the reactive power loss and increases the energy utilization at the same time [3-4].

In recent years, MPCC strategy has been widely used in the controller design of power electronic equipment, which is based on the discrete system model and the switch state determines by the evaluation function [5-10]. MPCC is easy to be digitized and it can realize the trace of reference. However, because the switching frequency is not fixed, the harmonic and EMI of the circuit is higher, which also makes it difficult to design a suitable filter. Based on that, some researchers proposed a fixed-frequency of MPCC control strategy to solve the problem [11]. Since power electronic equipment often has some nonlinear factors, it is often ignored in the controller design resulting in the generation of harmonics. When many power electronic devices connected to the microgrid, the generated harmonics will cause equipment damage, increase the reactive power loss and produce energy waste. For the model predictive current control, without a good matching degree of the model



it will lead to the circuit ripple becoming larger [12]. Therefore, the parameter identification of the circuit, especially, the online identification of a nonlinear inductor in the circuit, is also an important research area of model prediction [13-14] to improve the effectiveness of MPCC.

In this paper, an improved MPCC strategy is proposed to apply the bridgeless PFC circuit. Comparing with the traditional MPCC, the proposed MPCC has a fixed frequency of switch, which not only can reduce the harmonic of the current, but also reduce the EMI. In addition, in order to ensure good quality of current, the nonlinear problem of the inductor is also considered in this paper to reduce the prediction error because of the model's low-degree matching. Finally, the simulation and experimental results show the effectiveness of the proposed method.

2. Operation of dual boost bridgeless PFC converter

The dual boost bridgeless PFC converter is an improved topology of the boost converter, and the operation of converter is similar to the boost converter. The dual boost bridgeless PFC converter can work in four modes, and has strong advantages described as following:

- (1) Only one switch is involved in each loop, which reduces the conduction loss and there is no need for a drive isolation design;
- (2) The inductor has the characteristics of strong freewheeling capability and low current ripple;
- (3) The addition of two diodes can effectively reduce the common mode noise interference caused by the input and output.

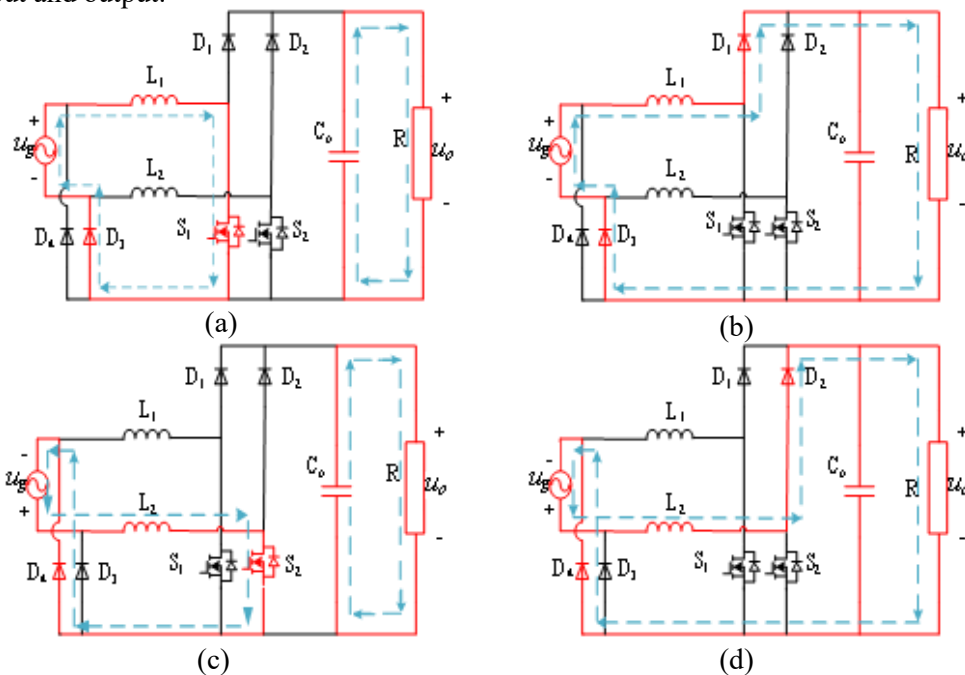


Figure 1. Operation principle of dual boost bridgeless boost PFC

Mode 1: The input power u_g is in the positive half cycle. With S_1 turned on, the inductor current is increasing. According to the Kirchhoff theory, the equation of circuit can be expressed as (1). The loop is composed of L_1 , S_1 and D_3 , and the output voltage is powered by C_o . The equivalent circuit is shown in figure 1(a).

$$L \frac{di}{dt} = u_g \quad (1)$$

Mode 2: The input power is in the positive half cycle. S_1 turned off, and the input source and charged inductance power the load and capacitance. The equation of circuit is shown in (2). Current through L_1 , D_1 , R and D_3 and the equivalent circuit is shown in figure 1(b).

$$L \frac{di}{dt} = u_g - u_o \quad (2)$$

Where u_o is the voltage of output.

Mode 3: The input AC voltage source is in the negative half cycle. S_2 turned on, the inductance current increased through L_2 , S_2 and D_4 . The load is powered by C_o . The equation of circuit is the same as equation (1), and its equivalent circuit is shown in figure 1(c).

Mode 4: The input power is in the negative half cycle. S_2 turned off, and the input source and charged inductance L_2 power the load and capacitance. Current through L_2 , D_2 , R and D_4 . The equivalent circuit is shown in figure 1(d).

3. Optimal MPCC strategy for the dual boost bridgeless PFC converter

The traditional model predictive control strategy predicts the current at next moment under the different switching state conditions; it compares the current $i(k+1)$ with the reference value, and it selects the switch state with less error or using evaluation function, which is shown in figure 2. The dual boost bridgeless PFC can be seen as a boost converter.

During the switch state, when the switch is on, the inductor is powered by AC voltage source. The equation of MPCC is shown as equation (3). When the state of switch is off, the relation of current and voltage is as shown in equation (4), and the inductor is demagnetized during the period. Because the inductance is a variable, L is replace by l to represent the nonlinearity of inductor.

$$\frac{di}{dt} = \frac{u_g}{l} \quad (3)$$

$$\frac{di}{dt} = \frac{u_g - u_o}{l} \quad (4)$$

If the switching frequency is high enough, the sampling period of the system is T_s , and the inductance current differential can be approximated as the following:

$$\frac{di}{dt} = \frac{i_L(k+1) - i_L(k)}{T_s} \quad (5)$$

Where T_s is the period of switch, i_L is the inductor current.

Based on that, the traditional MPCC strategy can be written as equation (6) and equation (7).

$$i_L(k+1) = T_s \times \frac{u_g}{l} + i_L(k) \quad (6)$$

$$i_L(k+1) = T_s \times \frac{u_g - u_o}{l} + i_L(k) \quad (7)$$

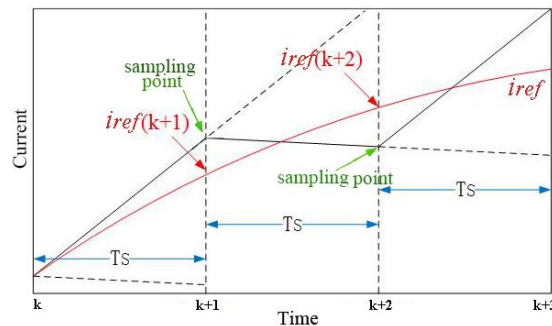


Figure 2. Traditional MPC control of a dual boost bridgeless PFC.

It can be observed that the model predictive control is a control strategy with an undefined frequency of the switching period. Therefore, the design of the filter is more difficult than other fixed-frequency methods for MPCC. In the earliest basic circuit, the duty cycle is to output the input power hierarchically. By combining this idea with the MPC control theory, an optimized MPC control

strategy with a fixed switching period is proposed, the input power is divided into m parts. Each duty cycle corresponds to l/m of input voltage as shown in figure 3.

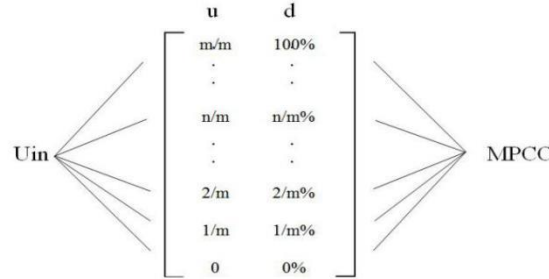


Figure 3. Optimal MPCC control with fixed frequency.

In the proposed MPCC control strategy, the period of control is a constant value. Under each control period, as equation (8) and equation (9) show, the MPCC algorithm predicts the current value at the next period, and using an evaluated formula to judge the state of switch in next control period, which is similar to the traditional MPCC algorithm.

$$i_L(k+1) = T_s \times \frac{D(k) \times u_g}{l} + i_L(k) \quad (8)$$

$$i_L(k+1) = T_s \times \frac{D(k) \times (u_g - u_o)}{l} + i_L(k) \quad (9)$$

An cost function is set as follow:

$$J = [i_{ref}(k+1) - i_L(k+1)]^2 \quad (10)$$

However, it can be seen from the formula above that there is a requirement of a high accuracy for the inductor. The nonlinear inductance, which has always been a difficult problem in the design of a controller for converters, also causes the controller difficult in achieving a good performance as the expectation. For a given inductor coil, the shape and size of the coil, the wire diameter of the wire, the number of turns, and the core are all determined. The value of the inductance is only related to the magnetic permeability μ of the core. When the inductance has a nonlinear behavior, a distorted current waveform is produced which causes serious damage to the grid and device. Based on the experimental measurement data, a formula of inductance with the change of current can be fitted as equation (11).

$$l = 0.0091 \times i_L(k)^2 - 0.4001 \times i_L(k) + 4.8904 \quad (11)$$

The comparison of the experiment data and the fitting curve is shown in figure 4.

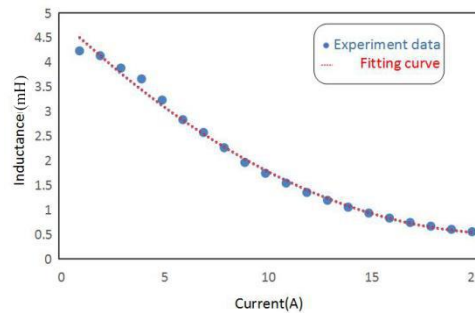


Figure 4. Comparison of experimental data and fitting curve.

4. Simulation and Experimental Test

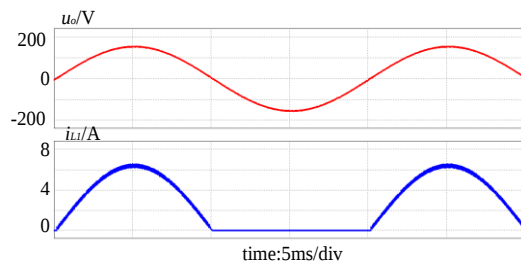
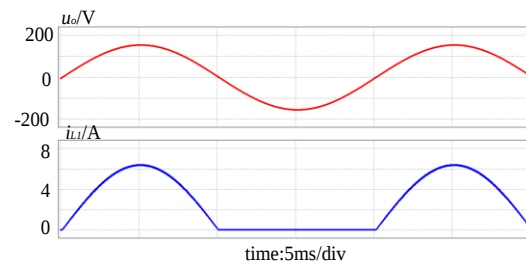
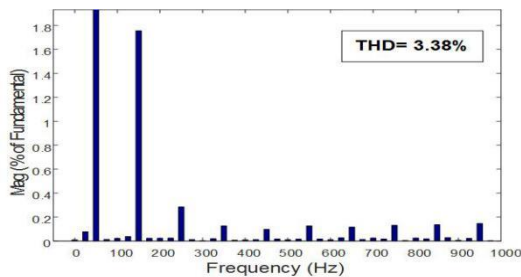
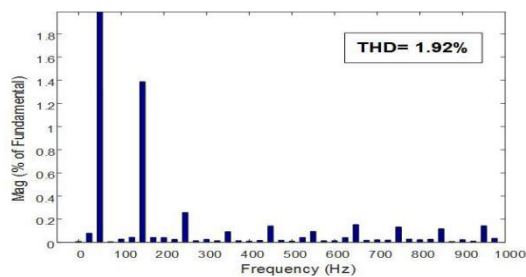
4.1. Simulation

In order to verify the correctness and feasibility of the proposed control strategy, a bridgeless PFC is built in Matlab software to simulate and compare the result of optimal MPCC with the traditional MPCC. A nonlinear bridgeless boost PFC is built according to the parameter set in table 1.

Table 1. Parameter of dual boost bridgeless PFC.

Parameter	value
DC Voltage(V)	380
AC Voltage(V)	220
Frequency of control(Hz)	50000
Rated power(W)	1000
Inductor(mH)	4
DC Filter Capacitance(μ F)	1000

The simulation results of traditional MPCC of the bridgeless boost PFC are shown in the figure 5, and the result of optimal MPCC is shown in figure 6, which proves the effectiveness of the proposed controller. The THD of traditional one is 3.38%, and the other one is 1.9%. The quality of current is improved.

**Figure 5.** Traditional MPCC simulation**Figure 6.** Improved MPCC simulation**Figure 7.** FFT analysis of traditional MPCC**Figure 8.** FFT analysis of improved MPCC

For the Fourier analysis of simulation, as shown in figure 7 and figure 8, it can be observed that the 3th harmonic reduced from 1.8% to 1.4%, and the quality of current is improved in the proposed control strategy.

4.2. Experimental test

In order to verify the correctness of the theoretical analysis, a prototype of 1000W bridgeless PFC was fabricated and controlled by the digital chip TMS320F28377D which is shown in figure 9.

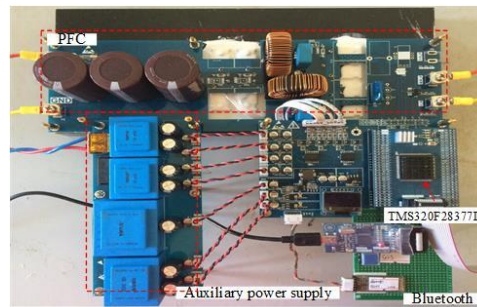


Figure 9. Experiment Prototype

Figure 10 shows the experimental waveforms of the output voltage u_o and the current i_L with the traditional MPCC strategy. The switching frequency is not fixed in a power frequency cycle. And, because there is no consideration of the inductor's nonlinearity, a large ripple affects the current quality.

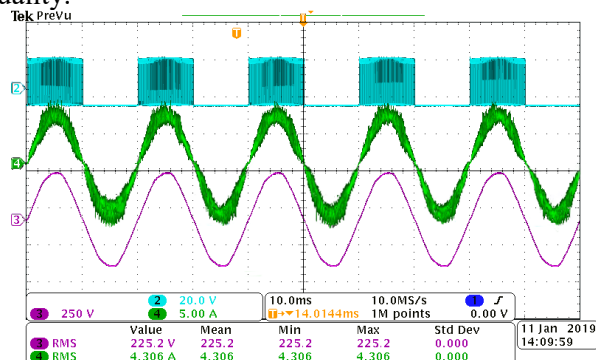


Figure 10. Traditional MPC control of dual boost bridgeless PFC

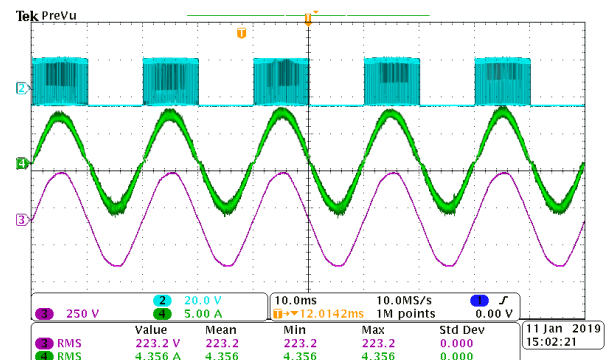


Figure 11. Optimal MPC control of dual boost bridgeless PFC

Figure 11 shows the experimental waveforms of the output voltage u_o and i_L with the improved MPCC strategy. As it can be seen from the results of figure 10 and 11, the inductance current ripple is obviously reduced. Using the proposed MPCC, it realizes the fixed frequency. With the consideration of the nonlinear inductor, the waveform of its current is improved.

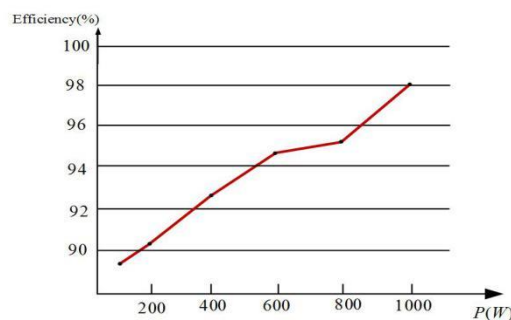


Figure 12. Efficiency at different load

The efficiency curve of the system is shown in figure 12. It can be seen the efficiency of the system shows a linear upward trend with the increase of power. The efficiency of the system is about 89% at a light load (100W). With the full load (1000W), the efficiency of system can reach 98%.

5. Conclusion

In this paper, an improved MPCC strategy is proposed to control the bridgeless boost converter. Compared with the traditional MPCC, the optimal MPCC has a fixed switching frequency which

makes it easy to design the filter. With the consideration of a nonlinear inductor, the error of current prediction is reduced by combining a nonlinear fitting formula with the experimental data of a nonlinear inductance. The simulation result shows the THD of current reduces from 3.8% to 1.9%. The prototype of a 1000W dual boost bridgeless PFC was fabricated, and the quality of its current and the power factor can be improved with the proposed control strategy.

Acknowledgements

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