Research on Model Predictive Control Strategy of Converter in Building DC Power Supply System

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Abstract. The popularization of distributed renewable energy, the change of end-user load characteristics, and the requirements of energy conservation and environmental protection have brought great challenges to the traditional AC power supply. Compared with AC power supply, DC power supply is widely concerned because of its powerful energy-saving advantages. Building electricity demand fluctuates greatly, and various power loads are frequently switched, which requires a higher demanding for the dynamic response capability. Based on switched system theory, this paper proposes a switched control method for building dc microgrid converter. The outer voltage loop adopts PI control and the inner current loop adopts predictive current control. The switched control model of the converter is established and the optimal switched rate is designed. An experimental platform based on SiC MOSFET is built for verification. The switched frequency is 50KHz, which verifies the effectiveness of the control strategy.

1. Introduction

In recent years, due to the energy crisis and the deterioration of the ecological environment, distributed power generation represented by photovoltaic has attracted extensive attention. Building energy consumption accounts for about 40% of the global total energy consumption [1], so buildings need to set up an energy-saving and efficient distribution architecture. Compared with AC microgrid, DC power supply can improve transmission efficiency, guarantee power quality, improve power supply reliability and reduce pollution, which has become a current research hotspot. It is expected that the proportion of DC load in China will reach 70% by 2050 [2]. The results of foreign studies show that the proportion of DC load in some types of buildings is even more than 90% [3].

At present, the research on topology and control of bi-directional DC/DC converter continues to deepen. Existing converters generally have low efficiency, large volume and other shortcomings, the application of SiC, GaN and other new high-frequency semiconductor devices can greatly improve the performance of the dual converter. Literature [4] used SiC staggered DC/DC converter with operating frequency of 100KHz to regulate the power output of proton membrane fuel cell, with a 95% operating rate. Literature [5] proposes a bi-directional AC/DC switched control method based on switched system theory. The system dynamic and static characteristics and dynamic characteristics under the control of switched algorithm are significantly better than the traditional PI control strategy. Literature [6] establishes the bi-directional DC/DC converter switched system model for energy storage and energy saving system, constructed the system's Lyapunov function, and deduces the

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system switched control law through Lyapunov function. Literature [7] further studies the design of stable switched law for switched systems, and carries out practical control for three typical dc–dc converters.

Due to the randomness of distributed power generation in the building dc micro-grid and the frequent switched of various dc loads such as air-conditioning and lighting, the dynamic response capability of the converter is highly required. At present, most research literatures on microgrid adopt small signal modelling method to analyse AC/DC converters and DC/DC converters [8–11]. The key points of DC microgrid energy balance control can be summarized as: voltage adjustment, voltage flicker, voltage sag, continuous interruption and harmonic content, etc [12–13]. Traditional double closed loop control has limitations on small signal modelling and may become unstable in the face of large signal disturbance. Based on the switched system theory, this paper directly models the large signal process of the system and establishes the converter switched system model. In addition, it also designs the optimal switched rate, carries out simulation and builds the building DC power supply experiment platform based on SiC MOSFET switch tube. The simulation and experiment results show that the modelling method and control strategy adopted are effective.

2. Building dc function system and converter model

2.1. Building dc power supply system and converter modelling

The building DC power supply reduces the AC/DC conversion process, without reactive power flow, reduces the loss of the line, eliminates the need to consider the complex control of frequency and phase in AC control, and saves the cost, and has been widely studied in recent years [14–17]. Document [18] chooses 220V and 48V dual bus structure to simulate. The total distribution efficiency of DC power supply system is about 93%. The main loss of distribution efficiency is the efficiency of AC/DC converter at municipal power grid access (95%). When the efficiency loss of AC/DC converter is not included, the distribution efficiency of DC distribution system is 97.9%. In literature [19], LVDC distribution network in ordinary high-rise buildings is studied, and it is concluded that the active power loss of distribution lines in dc distribution system is 4.11% less than that of ac system. Literature [20] modelled a 10-kw residential building, and concluded that the efficiency of 4.7% and 1.5% can be improved by using dc power supply system from the perspective of transmission and distribution respectively. Literature [21] compares the energy consumption of electrical appliances with the same power under the ac system and the dc system, as shown in table 1.

| Electrical parameters | Power (W) | Exchange total energy consumption(kW·h/a) | Total dc energy consumption (kW·h/a) |
|-----------------------|-----------|-------------------------------------------|-------------------------------------|
| Floodlight            | 60        | 700                                       | 61.32                               |
| The microwave oven    | 800       | 315.5                                     | 292                                 |
| The refrigerator      | 125       | 591.3                                     | 547.5                               |
| The washing machine   | 500       | 190.21                                    | 173.38                              |
| The notebook          | 50        | 139.25                                    | 127.75                              |
| Liquid crystal TV     | 156       | 315.90                                    | 284.7                               |
| A total of            |           | 2252.16                                   | 1486.65                             |

On the basis of traditional AC power distribution, a DC power distribution network is added to build a build-level DC microgrid system. Building DC microgrid can be connected to the grid or operated in island mode [22]. Building DC microgrid system is generally composed of AC/DC converter, DC/DC converter, DC bus, distributed power supply, DC load, energy storage device and other parts. At present, there is no technical standard for DC power supply in the world. The selection of voltage level varies from country to country. The working voltage range of each country is 200–400 V [23]. If the voltage level can be 380V/48V, etc., the 380V single-layer bus can provide power for the air-
conditioning and other high-power electrical appliances on the floor, and the 48V single-layer bus can provide power for LED lighting, computers, televisions and other low-power electrical appliances[24].

**Figure 1.** Topological structure of dc power supply system of the building

The efficiency of traditional AC transformer is up to 98%. Generally, the efficiency of IGBT DC converter and AC converter is about 85%-95%. Compared with AC power distribution, DC power distribution reduces dc-ac and AC/DC conversion links and improves the conversion efficiency of electric energy.

This paper studies the bi-directional AC/DC converter and bi-directional DC/DC converter of the architectural DC microgrid. The bi-directional DC/DC converter is connected to the DC bus and the battery and other energy storage devices. When the photovoltaic is insufficient, the battery will discharge, and when the photovoltaic is sufficient, the battery will charge. The battery requires high current ripple. Reducing current ripple can prolong the service life of the battery. The single-stage Boost converter has many problems, such as large ripple, slow response, high current and high voltage stress. The staggered Buck/Boost topology improves the output power, reduces the output voltage and current ripple [25], and reduces the volume of energy storage inductance and filter components. The main topology of the four-phase staggered bi-directional DC/DC converter is shown in figure 4.

The three-phase bi-directional AC/DC converter in the DC power supply system of the building is connected to the AC power grid and the DC bus. When the island is in operation, the AC/DC converter is in a state of shutdown. When it is connected to the grid, the energy flow in the AC power grid and the DC power supply system is controlled.

**Figure 3.** Four-phase interleaved bi-directional DC/DC converter

### 3. Control strategy of converter in building DC power supply system

#### 3.1 Repetitive switched control strategy for AC/DC converters

Firstly, the switching dynamic model of bidirectional AC/DC converter was established, the energy storage function of the system was selected as the common Lyapunov function, the optimal switching rate of the system was designed, and the stability of the system under the switching rate was analysed. Meanwhile, the switching strategy was discretized for easy operation.

Bidirectional way AC/DC structure shown as picture 5, thereinto, $E_a$, $E_b$ and $E_c$ are the three phase voltage at AC side; $i_a$, $i_b$ and $i_c$ are the three phase current; $U_{dc}$ is the voltage at DC side. $R$ and $L$ are the electric resistance and inductance of filtering reactor; $U_{in}$, $U_{iph}$ and $U_{ic}$ are the three phase voltage
dispersed signal of input commutator; C is the filtering electric capacity; k_p (p = a, b, c) represent the switch device status, k_p = 1 means the upper bridge arm of the p-pair switch is turned on, and the lower bridge arm is turned off; k_p = 0 means the upper bridge arm of the p-pair switch is turned off, and the lower bridge arm is turned on. 

Get the bidirectional AC/DC shifter current and voltage dynamic equation based on Kirchhoff’s voltage law.

\[
L \frac{d}{dt} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} E_a \\ E_b \\ E_c \end{pmatrix} - R \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} - \begin{pmatrix} U_{ra} \\ U_{rb} \\ U_{rc} \end{pmatrix}
\]

(1)

\[
\begin{pmatrix} U_{ra} \\ U_{rb} \\ U_{rc} \end{pmatrix} = \begin{pmatrix} K_a \\ K_b \\ K_c \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \frac{1}{3} \sum_{p=a,b,c} K_p \begin{pmatrix} U_{dc} \\ U_{dc} \\ U_{dc} \end{pmatrix}
\]

(2)

During the normal working process of bidirectional AC/DC shifter, k_a, k_b and k_c total corresponding 8 pieces valid switch assembly, means:000, 001, 010, 011, 100, 101, 110 and 111. Among, the same performance at 000 and 111, so define 7 types valid shift model status, means \( \{ x \in \{ 1,2,\ldots,7 \} \) , then system switch function can represented as:

\[
S_{p\sigma} = k_{pa} - \frac{1}{3} \sum_{p=a,b,c} k_{pa} \quad \sigma = 1,2,3,\ldots,7
\]

(3)

Where \( S_{p\sigma} \) represents the value of the P switch pair when switched to mode \( \sigma \).

The shift model of bidirectional AC/DC is:

\[
\dot{x}(t) = A_{\sigma} x(t) + B_{\sigma}
\]

(4)

In the formula (4), \( A_{\sigma} = \begin{pmatrix} -R & 0 & 0 \\ L & -R & 0 \\ 0 & L & -R \end{pmatrix} \), \( B_{\sigma} = \begin{pmatrix} E_{ra} - S_{ra} U_{dc} \\ L \frac{E_{rb}}{L} U_{dc} \\ L \frac{E_{rc}}{L} U_{dc} \end{pmatrix} \), \( x = \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \).

Quote theory 1: If all sub system of shifting system have collective Lyapunov function \( V(x) \), thereinto, \( V(0) = 0 \), and meet:

\[
\dot{V}(x) = \frac{\partial V(x)}{\partial x} f_{\sigma}(x) \quad \sigma = 1,2,\ldots, m
\]

(5)

then shifting system come to be stabilise at any shifting pathway.

To the bidirectional AC/DC, because it has energy save elements, so this article select it’s energy save function as collective Lyapunov function, set \( F = \text{diag}(L,L,L) \), then has the collective Lyapunov as follows:

\[
V(x-x^*) = (x-x^*)^T F(x-x^*)
\]

(6)

Designed shifting ratio:

\[
\sigma(x) = \arg \min_{\{ 1,2,\ldots, m \}} \{ \dot{V}(x-x^*) \}
\]

(7)
If can proof the whole running region of the shifting system all can be guaranteed under this shifting law, then means the shifting system will able to restrain to expected shifting balance points, and it is the quickest restrain speed.

Proof: A tau to satisfy all the vector \( \sum_{i=1}^{n} \beta_i = 1 \), \( 0 < \beta < 1 \) set, the convex combination of each subsystem is defined switched system for:

\[
\dot{x} = A_{eq} x + B_{eq}
\]

Make \( A_{eq} = \sum_{i=1}^{n} \beta_i A_i \), \( B_{eq} = \sum_{i=1}^{n} \beta_i B_i \) regard as the ratio of system continue performance time to the total shifting period, convex assembly can be understood as the average system of shifting form.

Make \( \delta = x - x^* \), formula (8) can changed to be:

\[
\dot{\delta}(t) = A_{eq} \delta(t) + B_{eq}
\]

In the formula (9), \( A'_{eq} = A_a, B'_{eq} = B_b = -\frac{L}{R^2} x^* - \frac{dx^*}{dt} \).

The derivative of shifting system’s collective Lyapunov function can be represented as:

\[
\dot{V}(\delta) = \delta^T F \delta + \delta^T F \dot{\delta} = (A_a \delta + B_a)^T F \delta + \delta^T F (A_b \delta + B_b)
\]

\[
= \delta^T (A_a^T F + F A_a) \delta + 2\delta^T F B_{eq}
\]

Make \( \sigma(X) = \arg \min_{i=1,2,...,7} [V(\delta)] \),

\[
\dot{V}(\delta) = \min_{i=1,2,...,7} [\delta^T (A_a^T F + F A_a) \delta + 2\delta^T F B_{eq}]
\]

\[
= \min_{i=1} [\delta^T (A_{eq}^T F + F A_{eq}) \delta + 2\delta^T F B_{eq}]
\]

We can know from the AC/DC shifting system model, no matter what are the selected value, always has: \( A_{eq}^T F + F A_{eq} = \text{diag}(-2R,-2R,-2R) < 0 \).

If we substitute \( x^* = (i_{eq}^*, i_b^*, i_c^*) \) into formula (9), we get:

\[
F_{B_{eq}} = \begin{pmatrix}
E_a - R_{eq}^* L \frac{di_{eq}^*}{dt} \\
E_b - R_{eq}^* L \frac{di_{eq}^*}{dt} \\
E_c - R_{eq}^* L \frac{di_{eq}^*}{dt}
\end{pmatrix} - \sum_{i=1}^{m} \beta_i k_{r \text{tot} i} \left( \begin{pmatrix}
E_a - R_{eq}^* L \frac{di_{eq}^*}{dt} \\
E_b - R_{eq}^* L \frac{di_{eq}^*}{dt} \\
E_c - R_{eq}^* L \frac{di_{eq}^*}{dt}
\end{pmatrix} - \sum_{i=1}^{m} \beta_i k_{r \text{tot} i} \right)
\]

We can know from the electric circuit characteristics of bidirectional AC/DC, when normally working, the voltage Udc of bidirectional AC/DC at DC side bigger than it’s voltage \( E_p (p=a,b,c) \) at AC side subtract the voltage reduce(voltage reduce on the electric resistance and inductance) on the circuit impedance, so it exist one group \( i(0<i<1) \), make \( F_{Beq} \leq 0 \), then can the \( 2\delta^T F B_{eq} \) \( \leq 0 \).

In summary, shifting law \( \sigma(x) = \arg \min_{i=1,2,...,7} [V(x-x^*)] \) able to guarantee the bidirectional AC/DC shifter gradually stable to the expected balance points.

Because the real-time calculation of the derivative value of Lyapunov function is large, it is necessary to discretize the switched rate. Set the AC/DC shifter adopt the fixed period T sampling, when the sampling period T is enough small, then has:
\[ \sigma(x) = \arg \min_{i \in \{2, \ldots, 7\}} \left\{ \bar{V}_i(x - x^*) \right\} \]
\[ = \arg \min_{i \in \{2, \ldots, 7\}} \left\{ \frac{V_i(x - x^*, t + \Delta T) - V_i(x - x^*, t)}{\Delta T} \right\} \]
\[ = \arg \min_{i \in \{2, \ldots, 7\}} \left\{ V_i(x - x^*, t + \Delta T) - V_i(x - x^*, t) \right\} \]
\[ = \arg \min_{i \in \{2, \ldots, 7\}} \left\{ \nabla_i (x_i(t + \Delta T) - x^*)^T F(x_i(t + \Delta T) - x^*) \right\} \]
\[ - (x(t) - x^*)^T F(x(t) - x^*) \]  \hspace{1cm} (10) \]

In the formula (10), \( x(t) \) is the real time sampling value at time \( t \), \( x^* \) is given, so the next item of formula (10) is the confirmed value, so the above formula can be further more simplified as:
\[ \sigma(x) = \arg \min_{i \in \{2, \ldots, 7\}} \left\{ \nabla_i (x_i(t + \Delta T) - x^*)^T F(x_i(t + \Delta T) - x^*) \right\} \]  \hspace{1cm} (11) \]

Solve the linear system status equation can get:
\[ x_i(t + \Delta T) = e^{\Delta t} x(t) + \int_{t}^{t+\Delta T} e^{\Delta \Delta t} B_{s} \varepsilon \, d\tau \]  \hspace{1cm} (12) \]

In the actually working, the sampling speed of AC/DC shifter is fast, can think they all are keep unchanged in one sampling period \( U(t) \) and \( E(t) \), so adopt the quotient difference of status variable replace the differential quotient to dispersed the above formula.
\[ x_i(t + \Delta T) = (I + A_{s}) x(t) + B_{s} \Delta T \]  \hspace{1cm} (13) \]

Establish the value function as follows:
\[ J_i = \left| x_i(t + \Delta T) - i^*_i \right| \quad i = 1, 2, 3, \ldots, 7 \]  \hspace{1cm} (14) \]

In formula (14), \( i^*_i \) is the current reference value of the outer voltage loop, and \( J \) is the difference between the predicted current value and the reference value at the next moment. For example, define the value function corresponding to \( S1=0, S2=0, S3=1 \) as \( J_3 \), then
\[ J_3 = \left| (I + A_{s}) x(t) + B_{s} \Delta T \right| - i^*_3 \]  \hspace{1cm} .In the formula,
\[ B_{s} = \begin{pmatrix} E_c + \frac{1}{3L} \\ \frac{E_c}{L} + \frac{1}{3L} \\ \frac{E_c}{L} + \frac{1}{3L} \end{pmatrix} \]

4. Simulated analysis
In Matlab/Simulink environment, a simulation model is built for the proposed method. During the simulation process, load is suddenly added and unloaded on the DC bus, and the simulation results are shown as follows.

4.1 Simulation of DC/DC converter
Simulation parameters of bidirectional DC/DC circuit are as follows: Filtering inductance \( L=5mH \); Sampling period \( T=10us \); DC bus capacitance \( C=6110uF \); The proportional constant \( Kp \) of the voltage outer loop PI regulator is 1, and the integral constant \( Ki \) is 5. The switched frequency is 50KHz.
Figure 4. Simulation results of two control methods

Figure 4 shows the simulation results of the two control methods in Boost mode. The load resistance is switched from 40 ohms to 20 ohms. The switched control method is compared with the traditional double closed loop control method, the DC bus voltage overregulation is reduced by 2%, the bus voltage dynamic response time is reduced by 0.05s, and the current and voltage ripple is significantly reduced.

Figure 5. Simulation results of two control methods

Figure 5 shows the simulation results of the two control methods when the converter Buck mode switches Boost mode. The bus voltage dynamic response time is reduced by 0.1s, and the current and voltage ripple is significantly reduced.

4.2 Simulation of AC/DC converter

Simulation parameters of bidirectional AC/DC circuit are as follows: Filter inductance L=0.5mH; Line impedance R=0.001, sampling period T=10us; DC bus capacitance C=6110uF; the proportional constant Kp of the voltage outer loop PI regulator is 1, and the integral constant Ki is 10; The switched frequency is 50KHz. When rectifying and inverting, the dc bus voltage Udc is 390V and 380V respectively. The network voltage is 380V/50Hz.

Figure 6 is the simulation result of load switched in rectifying mode. Udc in the figure is the voltage on the side of the dc bus, and Iabc is the three-phase current on the side of the power grid. Under the switched control strategy, the overshoot of bus voltage is less than 2.5%, and the dynamic response time is about 0.025s.

Figure 7 is the simulation result of rectifying mode switched inverter mode. In the simulation process, a 1KW load was suddenly added to the dc bus Udc, and the inverter mode was switched to the rectifier
mode. The voltage $U_{dc}$ of the dc bus was stable within about 0.01s, and the voltage fluctuation amplitude did not exceed 5%.

![Figure 6. Simulation results of dynamic response under rectifying mode](image)

![Figure 7. Simulation results of inverter mode switched rectifier mode](image)

5. Experimental verification
In order to verify the effectiveness of the switched control method, a SiC MOSFET-based converter building DC power supply experiment platform is built for verification and its . The experimental platform is composed of AC/DC converter, DC/DC converter, DC bus, DC load and other parts, and connected to the AC power grid, as shown in figure 8. The experimental parameters are the same as the simulation parameters.

![Figure 8. DC power supply experiment platform based on SiC MOSFET switch tube](image)

5.1 Experimental verification of DC/DC converter
5.1.1 Double closed loop experimental verification. Figure 9 and figure 10 are the input voltage of 12V respectively, the constant voltage output is 48V, the load mutates to the switched control waveform and conventional double closed loop control wave from 40 ohms to 20 ohms.
Figure 9. switched control waveform

Figure 10. Traditional double closed loop control waveform

Combined with figure 10 and figure 11, under staggered parallel topology, compared with traditional double-closed-loop control, the overregulation of DC bus voltage is reduced by 10%, the dynamic response time of DC bus voltage is reduced by 0.08s, the voltage and current ripple is significantly reduced, and the waveform of voltage and current is obviously better than that of single stage topology.

Figure 11. switched control waveform

5.1.2 Current loop experimental verification. Figure 11 and figure 12 respectively show the switched control waveform and the traditional double-closed-loop control waveform when the input current changes from 1.5a to 4A. Compared with the current response under the traditional control method
and the switched control strategy, and the dynamic response capacity and static characteristics of the system under the switched algorithm are significantly better than the traditional PI control strategy.

![Figure 12. Traditional double closed loop control waveform](image1)

5.2 AC/DC converter experimental verification

Figure 13 shows the switch control wave form when the load mutates from 40 ohms to 20 ohms under the condition of power line voltage of 380V and the DC bus constant voltage of 380V. When DC subnet load suddenly switch, DC bus voltage can be fast and stable, the maximum voltage fluctuation value is not more than 1%.

A sudden 1Kw load is applied to the converter, figure 14 is the waveform when the converter is switched from inverter mode to rectifier mode. The dc bus voltage $U_{dc}$ maintains a constant 380V. The current sinusoidal degree is good, and seamless switch between rectifier and inverter can be achieved.

![Figure 13. Rectifier mode switched control waveform](image2)

![Figure 14. Rectifier mode switched inverter mode experimental waveform](image3)

6. Conclusion

For building DC power supply system, this paper establishes a converter switched control model applies to building DC power supply system, and carries out simulation and experimental verification. Compared with the traditional control strategy, the switched control can accurately track the bus voltage given value, so that the bus voltage overshoot is greatly reduced and the dynamic response performance of the converter is greatly improved. In this paper, the control strategy proposed is more beneficial to describe the structure of power electronic circuit, which is easy to implement and has broad application prospects.
7. References

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