Study of Matrix Converter as a Current-Controlled Power Supply in QUEST Tokamak*)

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Because QUEST tokamak has a divertor configuration with a higher κ and a negative n-index, a precise power supply with a rapid response is needed to control the vertical position of the plasma. A matrix converter is a direct power conversion device that uses an array of controlled bidirectional switches as the main power elements for creating a variable-output current system. This paper presents a novel three-phase to two-phase topological matrix converter as a proposed power supply that stabilizes the plasma vertical position and achieves unity input power factor. An indirect control strategy in which the matrix converter is split into a virtual rectifier stage and a virtual inverter stage is adopted. In the virtual rectifier stage, the instantaneous active power and reactive power are decoupled on the basis of system equations derived from the DQ transformation; hence, unity power factor is achieved. Space vector pulse width modulation is adopted to determine the switching time of each switch in the virtual rectifier; the output voltage of the virtual rectifier is adjusted by the virtual inverter stage to obtain the desired load current. Theoretical analyses and simulation results are provided to verify its feasibility.

Keywords: matrix converter, unity power factor, vertical position instability, DQ transformation

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1. Introduction

Preventing plasma vertical position instability by controlling the stabilization coil current is essential for QUEST tokamak to achieve steady-state operation with a negative n-index [1]. The plasma vertical speed is as high as the poloidal Alfvén speed without a stabilizing shell, and for a negative n-index, the vertical instability of QUEST has a poloidal Alfvén time of several microseconds. The impedance of a stabilizing shell, which depends on its shape and thickness, is so large that the current induced in the stabilizing shell by the plasma's motion can produce a horizontal field that prevents vertical instability. For QUEST, if the thickness of the stabilizing shell is 1 mm, the temperature is 300°C, the elongation ratio κ is 2, and the n-index is −0.28, then the growth rate is 400 s^{-1} [1]. The vertical instability growth time increases from microseconds to milliseconds; this provides a premise for feedback control of the vertical instability. A high-speed, high-voltage inverter power supply is needed to compensate for the weakened horizontal field and control the plasma's vertical motion. In order to achieve a rapid response, the pulse width modulation (PWM) switching frequency of the power supply must be greater than the vertical instability growth rate of 400 s^{-1}. The PWM switching period is the dead time for feedback control of vertical instability and depends on the vertical instability growth rate; thus, the inverter power supply must have a PWM switching frequency of at least 4 kHz. The current depends on both plasma vertical growth rate and power limitation of the upper and lower horizontal field coils (HCU and HCL, respectively), so the current cannot exceed 2.5 kA. A unity power factor is not necessary in the power supply but is indispensable in the reactor.

A matrix converter is a type of rapid, precisely controlled power supply that is useful for achieving certain design conditions. It has the following desirable characteristics: generation of load voltage with an arbitrary amplitude and frequency; no need for a dc-link circuit; operation with unity power factor for any load; and regeneration capability [2, 3]. A three-phase to three-phase matrix converter was successfully constructed and simulated as a plasma control coil power supply [4]. A matrix converter with three input and output phases is currently of the greatest practical interest; sinusoidal input and output currents are required. Indirect and direct transfer function approaches

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are the two main types of control methods for matrix converters [4]. The indirect transform approach emulates a virtual voltage source rectifier and a virtual voltage source inverter. The direct transform approach is obtained by multiplying the transfer function of the voltage source rectifier and inverter; that is, the output phase voltage is synthesized directly by the input voltage and transform matrix.

Because of the power limitation of a bidirectional insulated gate bipolar transistor (IGBT) and the complexity of matrix converter control methods, the matrix converter is considered only as a power supply for vertical position control. For QUEST tokamak, the matrix converter is fed by a three-phase voltage source and two output phases that are connected to each end of the stabilization coils. The stabilization coil current must be controlled in order to eliminate the plasma vertical position instability. In this case, an arbitrary (non-sinusoidal) waveform for the coil current (i.e., the output current of the matrix converter) is proposed. On the other hand, the source's power factor must be maintained at unity.

A mathematical model of the power source and matrix converter was built on a DQ synchronous frame. Unlike the three-phase to three-phase matrix converter, the indirect transform approach consists of a three-phase virtual rectifier and a single-phase virtual inverter instead of a three-phase virtual rectifier and inverter. The active and reactive power are decoupled and controlled in the virtual rectifier stage, and the desired load current is introduced directly into the control block diagram of the virtual rectifier stage as the active current for unity power factor operation. A space vector PWM (SVPWM) algorithm was applied to obtain the virtual DC output voltage, and a common PWM algorithm was applied to the single-phase inverter stage.

2. Topology of Proposed Matrix Converter

Figure 1 illustrates the matrix converter topology for QUEST tokamak, where u_a, u_b, and u_c are the three-phase balanced source voltages, and v_a, v_b, and v_c are the input phase voltages for the matrix converter. The input filter consists of an inductor L_f and a capacitor C_f. "S" denotes the bidirectional switch, and the load is represented by the stabilization coils used to correct the plasma vertical position instability. The input filter can minimize the effect of unwanted harmonics from the load and avoid significant changes in the input voltages. The cutoff frequency of the input filter must be one decade above the power source frequency, but should also be less than the switching frequency [5]. A switching frequency of 10 kHz is assumed, and a cutoff frequency of 3 kHz is chosen. The inductance of L_f is set to 0.6 mH, and the capacitance of C_f is 4.7 µF. The rated input phase voltage and current are 700 V and 2.5 kA, respectively; the rated output voltage and current are 350 V and 2.5 kA, respectively. The relationship between the input voltages and output voltages can be expressed as (1) by using a set of switching states.

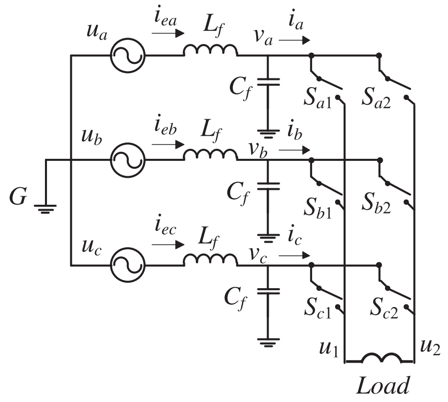

Fig. 1 Matrix converter topology for QUEST tokamak.

$$\begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} S_{a1}(t) & S_{b1}(t) & S_{c1}(t) \\ S_{a2}(t) & S_{b2}(t) & S_{c2}(t) \end{bmatrix} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} \quad (1)$$

Each switching state takes the value of either 1 or 0 in (1), representing the closed or open state of each bidirectional switch, respectively. The constraints can be expressed as

$$S_{ai} + S_{bi} + S_{ci} = 1,\ i = \{1, 2\} \quad (2)$$

Since the matrix converter is fed by a voltage source, the input phases must never be shorted; due to the inductive nature of the load, the output phases cannot be opened [2–4].

3. Control Strategy for Matrix Converter

Indirect modulation methods operate by splitting the modulation matrix in (1) into virtual rectifier and virtual inverter stages. The topology of the matrix converter in Fig. 1 is equivalent to the topology shown in Fig. 2. In the virtual rectifier stage, the output voltage is expressed as

$$\begin{bmatrix} V_{\mathrm{P}}(t) \\ V_{\mathrm{N}}(t) \end{bmatrix} = \begin{bmatrix} S_{a\mathrm{p}}(t) & S_{b\mathrm{p}}(t) & S_{c\mathrm{p}}(t) \\ S_{a\mathrm{n}}(t) & S_{b\mathrm{n}}(t) & S_{c\mathrm{n}}(t) \end{bmatrix} \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix}, \quad (3)$$

The load voltage of the virtual inverter stage is obtained by

$$\begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix} = \begin{bmatrix} S_{\mathrm{p}1}(t) & S_{\mathrm{n}1}(t) \\ S_{\mathrm{p}2}(t) & S_{\mathrm{n}2}(t) \end{bmatrix} \begin{bmatrix} V_{\mathrm{P}}(t) \\ V_{\mathrm{N}}(t) \end{bmatrix} \quad (4)$$

The capacity of C_f is quite small, and the input voltages of the rectifier can be expressed as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - L_f p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \quad (5)$$

where p represents the differential operator. The voltages and currents can be transformed to a synchronous frame by DQ transformation,

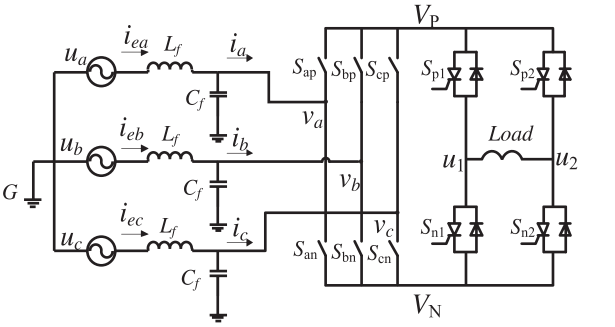

Fig. 2 Indirect matrix converter topology for QUEST.

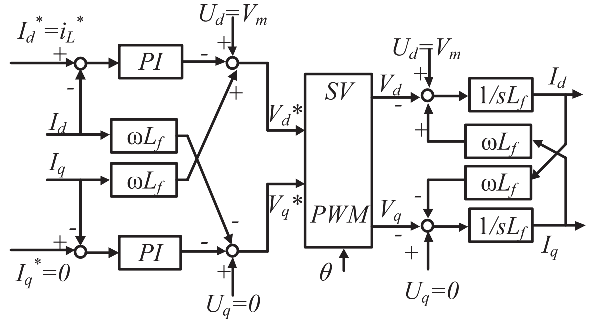

Fig. 3 Decoupled control block diagram for rectifier and input filter.

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2}{3}\pi\right) & \cos\left(\theta + \frac{2}{3}\pi\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2}{3}\pi\right) & -\sin\left(\theta + \frac{2}{3}\pi\right) \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}, \tag{6}$$

where f denotes the voltages and currents in (5), θ is the phase angle ($\theta=\omega t$), and the subscripts d and q represent the d and q axes, respectively, of the voltages and currents.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} U_d \\ U_q \end{bmatrix} - \begin{bmatrix} L_f p & -\omega L_f \\ \omega L_f & L_f p \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{7}$$

The active and reactive instantaneous power can be defined as [6]

$$P = \frac{3}{2}(U_d I_d + U_q I_q), \tag{8}$$

$$Q = \frac{3}{2}(U_q I_d - U_d I_q). \tag{9}$$

In general, the d and q components of the source voltages can be obtained from the balanced three-phase source voltages as

$$U_d = V_m,\ U_q = 0 \tag{10}$$

where V_m denotes the amplitude of the source phase voltages. The desired load current i_L^* represents a current vector consisting of two rotating orthogonal instantaneous current vectors,

$$i_L^* = \sqrt{I_d^{*2} + I_q^{*2}}, \tag{11}$$

and I_q^* must be 0 for unity power factor operation,

$$I_d^* = i_L^*,\ I_q^* = 0. \tag{12}$$

Equation (7) shows that mutual interference exists in the d-q current control loop, so a decoupling control algorithm is added to the design to address it. The current-decoupling control block diagram is shown in Fig. 3; and the currents along the q and d axes are decoupled and controlled by proportional integral (PI) controllers. The control block diagram for the rectifier and input filter can be simplified, as shown in Fig. 4.

The desired voltage vector in the synchronous frame consists of the voltage commands for the d and q axes,

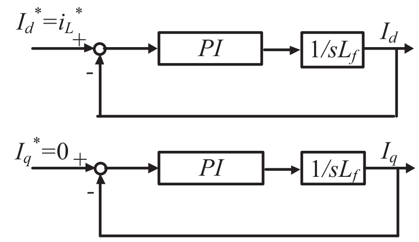

Fig. 4 Simplified control block diagram for rectifier and input filter.

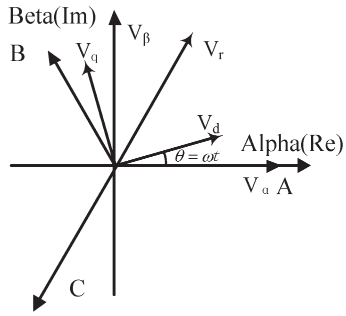

Fig. 5 Relationship among three-phase plane, complex plane, and synchronous frame.

V_d^* and V_q^*, respectively. They can be transformed to the complex plane by (13) in the SVPWM approach, where V_α^* and V_β^* represent the voltage commands of the real and imaginary components on the complex plane, respectively.

$$\begin{bmatrix} V_\alpha^* \\ V_\beta^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_d^* \\ V_q^* \end{bmatrix} \tag{13}$$

Figure 5 shows the relationship among the three-phase plane, complex plane, and synchronous frame. The space vector approach is based on the instantaneous space vector representation of the input and output voltages and currents. For unity power factor operation, the phase currents must be in phase with the input voltages; to achieve this, a voltage SVPWM algorithm is adopted. The rectifier switches can assume only six allowed combinations that yield nonzero output voltages and combinations of zero voltages [4]. The output voltage vector V_r is a combination of vectors V_d^* and V_q^* and rotates on the complex plane. Hence, V_r can be generated by the two adjacent active vectors of each sector and zero vectors. Consider the SVPWM algorithm shown in Fig. 6 as an example. In the current section, the modulated switches are S_{ap} and S_{bp}, and S_{cn} is kept closed; that is, S_{cn} is in non-modulated operation. Therefore, the limitation described by (2) is satisfied. The switching times of S_{ap} and S_{bp} are T_1 and T_2, respectively, and the switching time of S_{cn} is the sum of T_1 and T_2. The voltage vector V_1 is represented by the line voltage between phases A and C, and the voltage vector V_2 is represented by the line voltage between phases B and C. By the law of sines, the switching time is

$$\begin{aligned} T_1 &= T_s m_c \sin\left(\frac{\pi}{3} - \theta_r\right), \\ T_2 &= T_s m_c \sin\theta_r, \\ T_0 &= T_s - T_1 - T_2 \end{aligned} \tag{14}$$

where T_s is the switching cycle, T_0 is the switching time of the zero voltages, and m_c is the modulation index [7]. This index denotes the ratio between the peak values of the input currents and the DC output current magnitude of the rectifier, and is set to unity to obtain the maximum DC output voltage.

The control block diagram for the virtual inverter stage is shown in Fig. 7. The desired current is introduced to obtain the desired output voltage. The switching times S_{p1}, S_{p2}, S_{n1}, and S_{n2} can be obtained by a common PWM algorithm using the desired load voltage and virtual DC output voltage of the rectifier. The limitation mentioned in (2) is also guaranteed by the switching combinations of S_{p1}, S_{p2}, S_{n1}, and S_{n2}.

Finally, the total switching time of the bidirectional

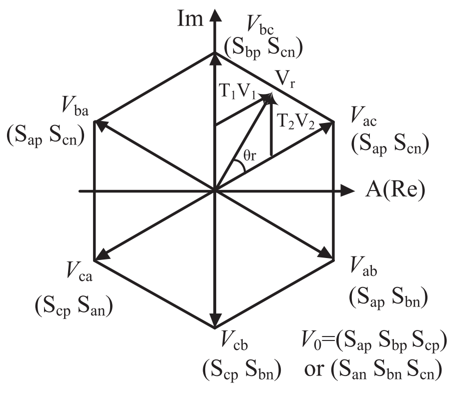

Fig. 6 SVPWM algorithm on the complex plane.

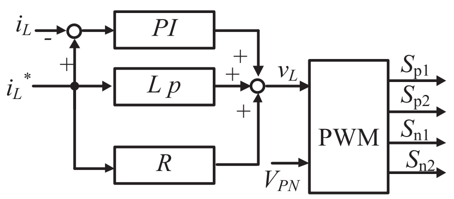

Fig. 7 Control block diagram for virtual inverter.

switches in (1) can be obtained by multiplying the switching matrices in (3) and (4). The limitation on (1) described by (2) is naturally satisfied because it is satisfied in both virtual rectifier stage and inverter stage.

4. Simulation Results

The matrix converter is considered as an actuator in the vertical instability control feedback loop. When the proportional gain is high, the required accuracy is not as important as the high-speed response. Ripples in the power supply disturb the horizontal magnetic field; furthermore, the plasma's vertical position control is disturbed, and a 1% ripple value in the load current will produce a 1% vertical position shock. Virtual dc-link voltages of the matrix converter adjacent to the output voltage reference are introduced to reduce the switching ripples in the output current. The ripple value of the load current is much smaller than 1% because of the high switching frequency (compared with other types of power supply) and the inductance of the HCU and HCL coils. The proposed topology was extensively investigated by simulations. The system parameters for the simulation are as follows. The input frequency was 60 Hz; the filter's inductance was 0.6 mH, and its capacitance was 4.7 μF; the amplitude of the source phase voltage was 1000 V, and the load's resistance and inductance were 5.27 mΩ and 1.199 mH, respectively. The response time must be smaller than the vertical instability growth time, and this was guaranteed by the switching frequency of the IGBT, which was set to 10 kHz. The desired current was set to rise linearly and then remain constant in order to achieve pulse mode operation. Assuming that the load current can rise to 2.5 kA in 5 ms, the step response time of the simplified control block diagram for the rectifier and input filter was set to 2 ms, and the proportional gain K_P and integral gain K_I of the PI controller in Fig. 4 were set to 0.52 and 300, respectively. For the inverter stage in Fig. 7, the proportional gain K_P and integral gain K_I of the PI controller were set to 0.27 and 1.07, respectively, to obtain a tradeoff between the parameter perturbation on L and R and the overshoot of the load current. Figure 8 shows that

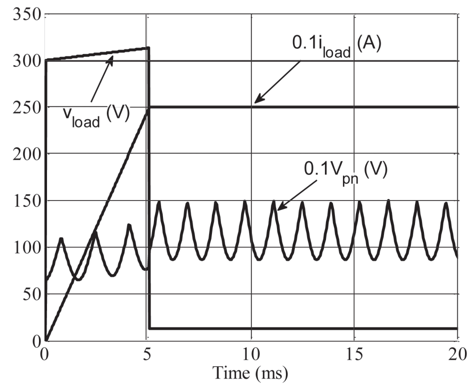

Fig. 8 Load current and voltage of matrix converter and output voltage of virtual rectifier.

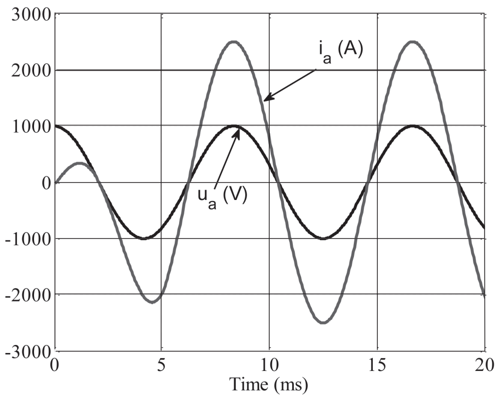

Fig. 9 Source voltage and current of matrix converter.

the load current increases from 0 to 2.5 kA in 5 ms and then remains constant. Although the output voltage of the virtual rectifier is rippled, the common PWM algorithm in the inverter stage can adjust the load voltage to obtain the desired load current. Figure 9 shows that the power factor is maintained at unity.

5. Conclusions

This paper presents a novel three-phase to two-phase matrix converter as a proposed power supply for correcting plasma vertical position instability in QUEST tokamak. The input filter was designed to prevent harmonics from the load and avoid significant changes due to the input voltages. An indirect control method was adopted to simultaneously achieve a unity input power factor and the output current needed to remove the plasma vertical position instability. A mathematical model of the matrix converter with a power source was obtained by DQ transformation, and the unity power factor was obtained by a decoupled closed loop of the *d*-axis and *q*-axis currents. SVPWM was adopted to determine the switching time of the switches in the rectifier stage. In the inverter stage, a common PWM was used to obtain the desired output voltage, which depends on the current needed to remove the plasma vertical position instability. Simulations indicate that the proposed matrix converter can be applied to plasma vertical position instability control in QUEST tokamak.

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