GTO PWM Current Source Converter Array For Superconducting Magnetic Energy Storage

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A novel multi modular GTO current source converter structure is presented to application to superconducting magnetic energy storage system. $N \times N$ converters are arranged in a array form. The GTO current source converter array with appropriate arrangement of modulation and carrier signals can output large power with high quality line current waveforms. With using of only N transformers, $6N^2$ pulse number converter performance is obtained. Only low switching of GTO is required since PWM is primarily used as a method to control flow of power instead of reducing harmonics. It is compared with conventional direct paralleled multi modular converter structure. The results of simulation are presented in this paper.

Key words: Multi modular Converters, PWM converters, High power converter, SMES, PWM

1. Introduction

High power converters with low harmonics are required for application in Superconducting Magnetic Energy Storage (SMES). GTOs are generally used because of high power. Switching frequency is restricted to a lower value. Multi converter modular combination structures have been used to reduce the harmonics and increase power capacity.[1] [2] Multi current source converter modular connecting structure can be classified as follows

- Method 1: AC sides of converter modular are paralleled through phase shifting transformers. DC side of converter modular are paralleled through current sharing inductors or seriesed directly.
- Method 2: AC sides of converter modular are directly connected with PWM carrier signal phases evenly shifted. [1] DC side of converter modular are paralleled through current sharing inductors, as shown in figure 1.

Method 2 is more advantage than Method 1 since transformers are not needed. Harmonics reduction of Method 2 is based on equal distant phase shifting of multi carriers. However in this condition generally average voltage of DC side of converter modular are not equal while the switching frequency is as low as 150Hz. DC side voltage of a converter can be described as

$$u_{dc} = Y_a u_a + Y_b u_b + Y_c u_c \quad (1)$$

where u_a , u_b , and u_c are input three phase voltage of converters, and Y_a , Y_b , and Y_c are switch control

functions of a converter. There are relationships between trilogic signal Y_a , Y_b , and Y_c , and bilogic signal X_a , X_b and X_c , i.e. $Y_a = (X_a - X_b)/2$, $Y_b = (X_b - X_c)/2$ and $Y_c = (X_c - X_a)/2$ [1]. It is assumed that three phase voltage are balanced. Carrier frequency ω_s is three times multiple of utility frequency ω . In this time Y_a , Y_b , and Y_c are balanced. Y_a can be described as $\sum_{n=2k+1}^{\infty} y_n \sin(n\omega t + \phi_n)$, where $k \geq 0$. Then $y_1 = \sqrt{3}x_1/2$ and $\cos\phi_1 = \cos(\phi_x + 30^\circ)$, where x_1 and ϕ_x is amplitude and phase angle of fundamental component of X_a . $X_a = \text{sign}[v_{ma}(\omega t + \phi_m) - v_c(\omega_s t + \phi_s)]$ where $\text{sign}(x) = 1$ if $x \geq 0$, $\text{sign}(x) = -1$ if $x < 0$. v_{ma} is the modulation wave of phase A and v_c is the carrier. The DC component of u_{dc} can be described by

$$\begin{aligned} U_{dc} &= \frac{1}{2\pi} \int_0^{2\pi} u_{dc} d\omega t = \frac{3}{2\pi} \int_0^{2\pi} Y_a u_a d\omega t \\ &= \frac{3}{2\pi} \int_0^{2\pi} U \sin(\omega t) \sum_{n=2k+1}^{\infty} y_n \sin(n\omega t + \phi_n) d\omega t \\ &= \frac{3y_1 U \cos\phi_1}{2} \\ &= \frac{3\sqrt{3}Ux_1 \cos(\phi_x + 30^\circ)}{4} \end{aligned} \quad (2)$$

Figure 1: SMES using direct paralleled four converters

Figure 2 shows variation of U_{dc} with changing of phase angle ϕ_s of the carrier. ω is utility frequency. The carrier frequency ω_s is selected to be 3ω . For a given group three modulation signals

$$v_{ma} = V_m \sin(\omega t + \phi_m)$$

$$v_{mb} = V_m \sin(\omega t + \phi_m - 120^\circ)$$

$$\text{and } v_{mc} = V_m \sin(\omega t + \phi_m - 240^\circ),$$

converter DC side output U_{dc} changes largely with the changing of the phase angle of the carrier.

Conventionally the amplitude V_m and phase angle ϕ_m of modulation waves are adjusted to make converter evenly sharing DC load current. At this time modulation signals of the paralleled converters become to be different. If there is no current sharing control, modulation signals for phase A of four paralleled converters are the same as shown in Fig.3(a). When a current sharing control is used, modulation signals for the paralleled converters differs as shown in Fig.3(b). Fig.2 is the result got from a case of direct paralleled four converters. As a result, harmonics cancellation originally expected can not be reached pronouncedly as

shown in Fig.4.

Figure 2: variation of U_{dc}/U caused by variation of carrier phase ϕ_s . Here — : $V_m/V_{cm}=1$; - - : $V_m/V_{cm}=0.75$; ... : $V_m/V_{cm}=0.5$; - · - : $V_m/V_{cm}=0.25$. (a) $\phi_m=0^\circ$; (b) $\phi_m=30^\circ$; (c) $\phi_m=60^\circ$; (d) $\phi_m=90^\circ$

Figure 3: modulation signals for phase A of direct paralleled four converters (a) without current sharing control (b) with current sharing control

2. Converter array

$N \times N$ number of converters are connected as shown in Fig.5. $N \times N$ converters arranged in a array form and connected in such a way that ac side of N number of converters in each row are paralleled and then connected to one phase shifting transformer, and dc side of N number of converters in each column serially connected and then connected to the load through a current sharing inductor. N transformers are used to generate evenly phase shifting isolated three phase voltage. The phase

shift of consecutive two transformers is $\Delta\phi = 60^\circ / N$.

Figure 4: one phase current of direct paralleled four converters with current sharing control (a) one phase current (b) its harmonic spectrum

Figure 5: converter array

Therefore current harmonics less than $6N \pm 1$ are completely eliminated. Each transformer is paralleled with N converters. A converter in i row and j column is marked as $\text{Conv}(i, j)$. Operation of $\text{Conv}(i, j)$ is decided by its modulation signals and its carrier. Three phase modulation signals of a converter are balanced. The phase A modulation signal of $\text{Conv}(i, j)$ is selected as

$$V_{mij}^a = V_m \sin(\omega t + \phi_m + \beta_{i,j}) \quad (3)$$

The carrier wave of $\text{Conv}(i, j)$ is defined

$$V_{cij} = V_c \left(\omega_s t + \frac{\omega_s}{\omega} \beta_{i,j} \right) \quad (4)$$

and

$$\beta_{i,j} = (i-1)\Delta\phi + [i+j-2]_N \Delta\psi \quad (5)$$

where $V_c(\omega_s t)$ is triangle carrier wave, and $\Delta\psi = \frac{\Delta\phi}{N}$. $[i+j-2]_N$ is defined as $(i+j-2) \bmod N$. With above mentioned modulation waves and carriers used, three phase ac current waveforms of converters in the same row are the same except for phase shift.

Phase A current of converter module $\text{Conv}(i, j)$, $i_a^{(i,j)}$ is

$$i_a^{(i,j)} = I_{dcj} Y_a^{(i,j)} = \frac{I_{dc}}{2N} \left(X_a^{(i,j)} - X_b^{(i,j)} \right) \quad (6)$$

Where it is assumed that DC side current I_{dc} is evenly supported by N paralleled output branches, i.e. $I_{dcj} = I_{dc}/N$. Phase A current of transformer i can be described by

$$i_a^{(i)} = \sum_{j=1}^N i_a^{(i,j)} = \frac{I_{dc}}{2N} \left[\sum_{j=1}^N X_a^{(i,j)} - \sum_{j=1}^N X_b^{(i,j)} \right] \quad (7)$$

Since $X_a^{(i,j)} = \text{sign}(V_{mij} - V_{cij})$, $i_a^{(i)}$ can be expressed as

$$\begin{aligned} i_a^{(i)} &= \frac{I_{dc}}{2N} \left(\sum_{j=1}^N \text{sign}(V_m \sin(\omega t + \phi_m + (i-1)\Delta\phi \right. \\ &\quad \left. + [i+j-2]_N \Delta\psi) - V_c(\omega_s t + \frac{\omega_s}{\omega} ((i-1)\Delta\phi \right. \\ &\quad \left. + [i+j-2]_N \Delta\psi)) - \sum_{j=1}^N X_b^{(i,j)} \right) \\ &= \frac{I_{dc}}{2N} \left(\sum_{k=0}^{N-1} \text{sign}(V_m \sin(\omega t + \phi_m + (i-1)\Delta\phi \right. \\ &\quad \left. + k\Delta\psi)) - V_c(\omega_s t + \frac{\omega_s}{\omega} ((i-1)\Delta\phi + k\Delta\psi)) \right. \\ &\quad \left. - \sum_{j=1}^N X_b^{(i,j)} \right) \end{aligned} \quad (8)$$

Therefore

$$i_a^{(i+1)}(\omega t) = i_a^{(i)}(\omega t + \Delta\phi) \quad (9)$$

That means that secondary side currents of transformer i is shifted from secondary side currents of transformer $(i+1)$ by angle $\Delta\phi$. Further the phase current of secondary side of each transformer is a sum of N evenly phase shifted currents from N converters in one the same row. Therefore $N \times N$ converter array is equivalent to $6N^2$ pulse number converter. Current harmonics in ac side is considerably reduced.

DC side voltage of a converter $\text{Conv}(i, j)$ is

$$\begin{aligned} u_{dc}^{(i,j)} &= Y_a^{(i,j)} u_a^{(i)} + Y_b^{(i,j)} u_b^{(i)} + Y_c^{(i,j)} u_c^{(i)} \\ &= -\frac{1}{2} (X_a^{(i,j)} v_{ca}^{(i)} + X_b^{(i,j)} v_{ab}^{(i)} + X_c^{(i,j)} v_{bc}^{(i)}) \end{aligned} \quad (10)$$

Sum of DC side voltage of a column of converters is

$$u_{dc}^{(j)} = \sum_{i=1}^N u_{dc}^{(i,j)} = -\frac{1}{2} \sum_{i=1}^N (X_a^{(i,j)} v_{ca}^{(i)} + X_b^{(i,j)} v_{ab}^{(i)} + X_c^{(i,j)} v_{bc}^{(i)}) \quad (11)$$

The dc component of $u_{dc}^{(j)}$ is

$$\begin{aligned} U_{dc}^{(j)} &= \frac{1}{2\pi} \int_0^{2\pi} u_{dc}^{(j)} d\omega t \\ &= -\frac{3}{2} \sum_{i=1}^N \int_0^{2\pi} X_a^{(i,j)} v_{ca}^{(i)} d\omega t \\ &= -\frac{3}{2} \sum_{i=1}^N \int_0^{2\pi} \text{sign}(V_m \sin(\omega t + \phi_m \\ &\quad + (i-1)\Delta\phi + [i+j-2]_N \Delta\psi) \\ &\quad - V_c(\omega_s t + \frac{\omega_s}{\omega} ((i-1)\Delta\phi + [i+j-2]_N \Delta\psi))) \\ &\quad \sqrt{3}U \sin(\omega t - 240^\circ + 30^\circ + (i-1)\Delta\phi) d\omega t \\ &= -\frac{3}{2} \sum_{k=0}^{N-1} \int_0^{2\pi} \text{sign}(V_m \sin(\omega t + \phi_m + k\Delta\psi) \\ &\quad - V_c(\omega_s t + \frac{\omega_s}{\omega} k\Delta\psi)) \sqrt{3}U \sin(\omega t - 210^\circ) d\omega t \end{aligned} \quad (12)$$

Figure 6: two columns automatically share the current of superconducting magnetic coil

$U_{dc}^{(j)}$ is independent of j . Therefore average voltage of each column of converters is the same. It means that paralleling of output side of columns of converters is possible. Fig.6 shows dc side output currents of two columns of converters in 2×2 converter array when no current sharing control is used. DC side currents are automatically balanced.

3. Harmonic characteristics of converter array

A 2×2 converter array used in SMES is shown in Fig.7.

Figure 7: SMES using converter array

A Δ/Δ transformer and a Δ/Y transformer is used to generate phase shifted ac voltages. Phase shift $\Delta\phi = 30^\circ$. The inter-phase reactors are 0.1H. Its modulation signals and carrier signals are arranged as shown in Fig.7. Fig.8 shows AC side current of the converter array. Fig.9 and Fig.10 show a phase current on utility line and its spectrum. The inductance of superconducting magnetic coil L_{SMC} is 40H. The initial current of it is 1000A. The amplitude of the phase voltage of the utility is 1000V. The carrier frequency is 150Hz and utility frequency is 50Hz. Two transformers are used to eliminate 5th and 7th harmonic. 11th and 13th is considerably reduced through phase shifting of both carrier and modulation signal among converters. DC voltage unbalance is overcome by serially connected DC side of two converter.

For comparison Fig.11 and Fig.12 shows one phase current of conventional direct paralleled four converters. Carriers for these four converters are evenly shifted by 45° to eliminate $6n \pm 1$ harmonics where $n=1, 2$, and 3. Modulation signal amplitudes are controlled to evenly share SMES coil current. The initial energy of L_{SMC} is the same as that of the 2×2 converter array. The initial current of the superconducting magnetic coil is selected to be 2000A so that the current capacity of each

converter modular is the same as that of each converter modular of 2×2 converter array. At this time $L_{SMC}=10H$. From Fig.11 and 12 it can be found that both amplitudes and phases of modulation waves are varied and they are not the same any more. As a result harmonics can not be eliminated each other effectively. There are 5th, 7th, 11th, 13th, 17th, and 19th harmonic current components.

Figure 8: AC side currents of 2×2 converter array (a) phase A current of AC side of modular converter Conv(1,1) (b) phase A current of Ac side of modular converter Con(1,2) (c) phase A current of Ac side of modular converter Con(2,1) (d) phase A current of Ac side of modular converter Con(2,2) (e) phase A voltage and current of AC side of the converter array

Figure 9: 2×2 converter array with $P= -1MW$ and $Q= -0.5MVar$ (a) phase A modulation signals of four converters (b) a phase current (c) harmonic spectrum

of a phase current

Figure 10: 2×2 converter array with $P= -2MW$ and $Q=0MVar$ (a) phase A modulation signals of four converters (b) a phase current (c) harmonic spectrum of a phase current

Figure 11: direct paralleled four converters with $P= -1MW$ and $Q= -0.5MVar$ (a) phase A modulation signals of four converters (b) a phase current (c) harmonic spectrum of a phase current

New proposed converter array has less low frequency harmonics than the conventional direct paralleled converter structure. 2×2 array converter is approximate to a 24 pulse number converter in respect to reduction of harmonics.

Figure 12: direct paralleled four converters with $P = -2\text{MW}$ and $Q = 0\text{MVar}$ (a) phase A modulation signals of four converters (b) a phase current (c) harmonic spectrum of a phase current

4. SMES using 2×2 converter array

The proposed converter is able to work at full P-Q plane. It can generate both active power and reactive power.

4.1 Active and reactive power control

By using the new converter shown in Fig.5 active power and reactive power control is carried out. Fig.13 shows power tracking process. Fig.13(a) shows voltage and current of phase A of the converter array. Fig.13(b) gives power and reactive power generated by the converter array. Fig.13(c) shows decaying current of the superconducting magnetic coil L_{SMC} because of discharge of magnetic energy.

4.2 Maximum power

The upper limit power which can be output by a $N \times N$ converter array can be estimated as

$$P_{\text{max}} = N^2 \times U_{\text{dc max}} I_{\text{dc}} \quad (13)$$

where $U_{\text{dc max}}$ is maximum value of DC side average voltage of a converter module and I_{dc} is DC side average current of a converter module. In addition $I_{\text{dc}} = I_{\text{smc}} / N$ and I_{smc} is the current of superconducting magnetic coil. $U_{\text{dc max}}$ is able to be calculated as

$$U_{\text{dc max}} = 1.65 U_{\text{am}} \quad (14)$$

where U_{am} is the amplitude of the phase voltage of the

utility. Therefore

$$P_{\text{max}} = 1.65 N U_{\text{am}} I_{\text{smc}} \quad (15)$$

For the 2×2 converter array shown in Fig.7, maximum power can be estimated by

$$P_{\text{max}} = 1.65 \times 2 \times 1000\text{V} \times 1000\text{A} = 3.3\text{MW} \quad (16)$$

Figure 13: Active power and reactive power control process (a) phase voltage and current of AC side of the converter array (b) active and reactive powers generated by the converter array (c) the current of L_{SMC}

Figure 14: 2×2 converter array in maximum power output state (a) maximum power (b) a line current (c) its spectrum

Figure 15: direct paralleled four converters in maximum power output state (a) maximum power (b) a line current (c) its spectrum

Since there exist phase shifting among modulation signals in the same row of a $N \times N$ converter array, it is impossible to force all converters at the same row to output maximum voltages. Maximum power a converter array can output is always less than the upper limit value given above. Fig.14(a) shows maximum power which can be output by the 2×2 converter array. Fig.14(b) and (c) shows a line current and its spectrum. For comparison Fig.15(a) shows maximum power which can be output by direct paralleled four converters. Fig.15(b) and (c) show a line current and its spectrum. It means that capacity of the switching devices in the converter array are effectively used.

5. Conclusion

GTO current source converter array with appropriate arrangement of modulation and carrier signals can output large power with high quality current waveform. A $N \times N$ converter array is similar to a $6N^2$ pulse number converter in respect to harmonic performance. low switching of GTO is required since PWM is primarily used as a method to control flow of power instead of reducing harmonics. The capacity of the switching devices in the converter array is effectively used.

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