IEEE 1999 International Conference on Power Electronics and Drive Systems, PEDS'99, July 1999, Hong Kong.

Adaptive B-Spline Network Control for Three-Phase PWM AC-DC Voltage Source Converter

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Abstract— A neural network control method – adaptive B-spline neural network for three-phase AC-DC voltage source converters that realizes a sinusoidal ac input current and unity power factor is discussed in this paper. Comparing to the other PWM techniques, the main advantage of the neural network is that it has excellent merit for nonlinear control and is adaptive enough to fit the environment change. Since the training for the network is on-line in this paper, it is more robust to external disturbances. B-spline neural network is used because it is characterized by a local weight updating scheme with the advantages of fast convergence speed and low computation complexity. This is fairly important for real-time control application. The stability of the network control strategy can be shown using Lyapunov law. Simulation results are presented to illustrate the effectiveness of the proposed control strategy.

I. INTRODUCTION

In recent years, there has been a tendency to operate the AC-DC converters with the PWM switching pattern that improve the input and output performance of the converter. Compared with the widely used phase-controlled converter, PWM converter can deliver the near-sinusoidal input current at unity power factor [1]. The performance of the converter system largely depends on the quality of the applied control method. Various control methods have been proposed for voltage-source converter. The main objectives in the control of the PWM AC-DC converters are to achieve a high power factor and minimum harmonic distortion of the input current. For some high-performance applications, such as airplane, high precise controller is necessary for the converters. The nonlinear controller is more suitable than the linear controller since the converter is truly a nonlinear system. The ability of neural networks to approximate various complex nonlinear functions relating input-output data from a nonlinear system has attracted many researchers [2] [3]. This paper explores the utilization of B-spline neural network in PWM AC-DC converters. Same as other neural networks, B-spline neural network can also approximate continuous functions at any arbitrary accuracy as long as the network is large enough [4]. Unlike the global weight updating scheme used in backpropagation-based neural networks, B-spline neural network is characterized by a local weight updating scheme with the advantages of fast convergence speed and low computation complexity. These characters make it more suitable for the on-line and adaptive situations.

In this paper a B-spline neural network is used to design the control strategy for a three-phase PWM AC-DC Voltage Source Converter. The on-line learning algorithm is proposed for the network and the stability of the entire control scheme is shown using Lyapunov Law. Computer simulations have proved that the system with the proposed control strategy not only guarantees the good stability, but also provides good transient response, and unity power factor.

II. MATHEMATICAL MODEL

The main circuit of the PWM AC-DC voltage source converter that is discussed in this paper is as in Fig. 1. The source voltage is assumed to a balanced, sinusoidal three-phase voltage supply with frequency ω as follows:

$$\begin{aligned} e_a &= E_m \cos(\omega t) \\ e_b &= E_m \cos(\omega t - \frac{2\pi}{3}) \\ e_c &= E_m \cos(\omega t + \frac{2\pi}{3}) \end{aligned} \tag{1}$$

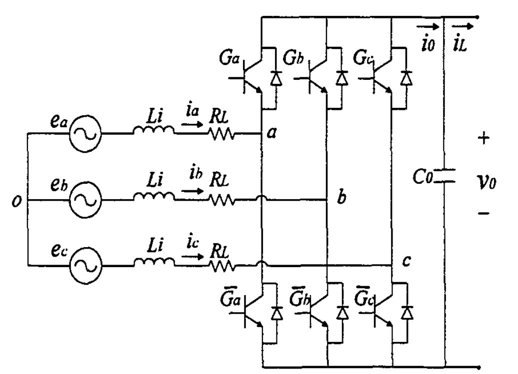

Fig.1 Schematic of three-phase ac-dc voltage source rectify

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where e_a, e_b and e_c are three phase voltage, E_m and ω are the amplitude of the phase voltage and angular frequency of the power source, respectively. The voltage equation of Fig. 1 is

$$\bar{e} = L_i \frac{d}{dt}\bar{i}_s + R_L \bar{i}_s + \bar{v}_s \tag{2}$$

where

$$\bar{e} = [e_a \quad e_b \quad e_c]^T$$

$$\bar{i}_s = [i_a \quad i_b \quad i_c]^T$$

$$\bar{v}_s = [v_{ao} \quad v_{bo} \quad v_{co}]^T$$

Transform the above three-phase variables into d-q coordinate system which rotates at the source angular frequency ω for the convenient of modeling and control design.

Transformation matrix is given as T:

$$T = \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \tag{3}$$

Suppose

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = \frac{2}{3} T \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad \begin{bmatrix} s_d \\ s_q \end{bmatrix} = \frac{2}{3} T \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix}$$

where s_a, s_b and s_c are the bipolar switching functions describing as the following.

$$s_j = \begin{cases} 1 & \mathrm{G_j\ closed} \\ -1 & \bar{\mathrm{G}}_j\ \mathrm{closed} \end{cases} \qquad \mathrm{j = a, b, c}$$

After the above transform, we can obtain d-q equations for the converter as following:

$$L_i \frac{di_d}{dt} = \omega L_i i_q - R_L i_d - \frac{1}{2} v_0 s_d + E_m \tag{4}$$

$$L_i \frac{di_q}{dt} = -\omega L_i i_d - R_L i_q - \frac{1}{2} v_0 s_q \tag{5}$$

$$C_0 \frac{dv_0}{dt} = \frac{3}{4}(s_d i_d + s_q i_q) - \frac{v_0}{R_0} \tag{6}$$

where R_0 is the load resistance and $i_L = \frac{v_0}{R_0}$ is the load current. Note for simplicity to illustrate, we do not consider inductor resistance or capacitor resistance here. However it is not difficult to expand the result to those conditions. More details about this transformation can refer to [5]. From equation (4) to (6) we can know that the system is nonlinear since s_d and s_q are control variables.

In order to obtain the unity power factor, it is required that i_q to be zero (in steady state) and i_d corresponds to the magnitude of the input line current I_m which is given as following equation [5].

$$I_m = \frac{1}{2}\left[\frac{E_m}{R_L} + \sqrt{(\frac{E_m}{R_L})^2 - \frac{8V_r i_L}{3R_L}}\right] \tag{7}$$

And it has also assumed that steady output voltage is controlled to be the fixed voltage V_r.

The space-vector PWM method (SVPWM) is used to determine the switching functions, and the switching function space vector is defined as:

$$S = \frac{2}{3}(S_a + uS_b + u^2 S_c) \tag{8}$$

where $u = e^{j(2\pi/3)}$ and is known as Park's vector. Since the switching functions are bipolar, equation (8) can be written in the generalized form for all rectifier switching states as follows:

$$S_n = \begin{cases} \frac{4}{3} e^{j(n-1)\pi/3} & n = 1,2,...,6 \\ 0 & n = 7,8. \end{cases} \tag{9}$$

In Fig.2 these eight vectors are shown. This vector method is often used in PWM converter control.

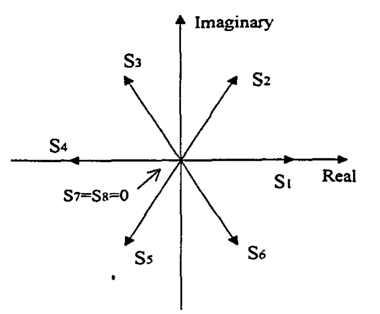

Fig.2 Rectifier switching function space vectors

Let T_s denotes half the switching period. That is, $T_s = 1/(2f_{sw})$, where f_{sw} is the rectifier switching frequency. In order to minimize the ripple content of the line current, the time spent on the zero state is equally distributed at the beginning and the end of the T_s period. The switching order for three-phase voltage and the definitions of T_0, T_n, and T_{n+1} are illustrated in Fig.3.

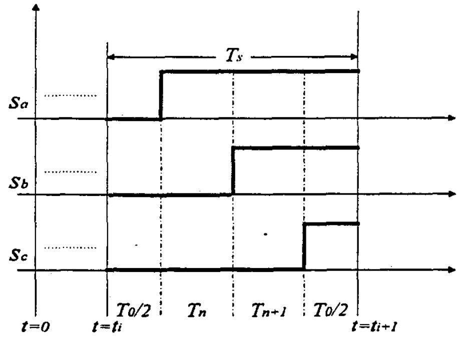

Fig. 3 Scheme of SVPWM

According to [5], T_n and T_{n+1} can be determined in the following.

$$T_n = \frac{1}{\Gamma_{n(n+1)}}[S_{(n+1)q}s_d^s - S_{(n+1)d}s_q^s]T_s$$

$$T_{n+1} = \frac{1}{\Gamma_{n(n+1)}}[S_{nd}s_q^s - S_{nq}s_d^s]T_s$$

where $\Gamma_{n(n+1)} = S_{nd}S_{(n+1)q} - S_{nq}S_{(n+1)d}$ and S_{nd}, S_{nq} are real and imaginary components of S_n respectively. s_d^s and s_q^s are defined as

$$s_d^s = s_d \cos(\omega t_i) - s_q \sin(\omega t_i)$$

$$s_q^s = s_q \cos(\omega t_i) + s_d \sin(\omega t_i)$$

III. CONTROL STRATEGY

In this section we develop a control strategy based on adaptive on-line B-spline network. We use two-dimensional multivariate basis functions formed from two, order 2, univariate basis functions in the control. Univariate basis function of order 2 is shown in Fig. 4. The objectives of this control strategy are to drive the dc-output voltage v_0 to the reference voltage V_r, and also provide unity power factor with near sinusoidal input line current. For the B-spline neural network, interested readers can refer to the book [4]. The B-spline neural network can be described as

$$f(x) = \sum_{i=1}^{n} w_i \sigma_i(x) \tag{10}$$

where w_i and σ_i are weight and B-spline function respectively. And n is the number of weights.

Suppose

$$W = [w_1 \ \ w_2 \ \ \cdots \ \ w_n]^T \qquad \sigma = [\sigma_1 \ \ \sigma_2 \ \ \cdots \ \ \sigma_n]^T$$

equation (1) can be simply expressed as

$$f(x) = W^T \sigma(x) \tag{11}$$

In the converter, two B-spline networks are used. They can be described as following:

$$\Delta s_d = W_1^T \sigma_1(i_d, i_q, v_0) \tag{12}$$

$$\Delta s_q = W_2^T \sigma_2(i_d, i_q, v_0) \tag{13}$$

On the basis of the Lyapunov stability theory, define a positive scalar function candidate as

$$V(x) = \frac{3}{2}L_i x_1^2 + \frac{3}{2}L_i x_2^2 + C_0 x_3^2 + \frac{1}{2}W_1^T W_1 + \frac{1}{2}W_2^T W_2 \tag{14}$$

where x_1, x_2 and x_3 are described as

$$x_1 = i_d - I_m \qquad x_2 = i_q \qquad x_3 = v_0 - V_r$$

Taking the derivative of equation (14) and substituting equation (4) (5) (6) and (7) into it, we can obtain

$$\dot{V}(x) = -\frac{3}{2}(V_r x_1 - I_m x_3)\Delta s_d - \frac{3}{2}V_r x_2 \Delta s_q - 3R_L(x_1^2 + x_2^2) + W_1^T \dot{W}_1 + W_2^T \dot{W}_2 \tag{15}$$

Because of equation (12) and (13), equation (15) change to be

$$\dot{V}(x) = -\frac{3}{2}(V_r x_1 - I_m x_3)W_i^T \sigma_1 - \frac{3}{2}V_r x_2 W_2^T \sigma_2 - 3R_L(x_1^2 + x_2^2) + W_1^T \dot{W}_1 + W_2^T \dot{W}_2 \tag{16}$$

Now if we choose the learning algorithm for the weights of the networks as the following two equations

$$\dot{W}_1 = \frac{3}{2}(V_r x_1 - I_m x_3)\sigma_1 \tag{17}$$

$$\dot{W}_2 = \frac{3}{2} V_r x_2 \sigma_2 \tag{18}$$

then the equation (16) change to be

$$\dot{V}(x) = -3R_L(x_1^2 + x_2^2) \tag{19}$$

It is obvious that equation (19) will always be no more than zero. From equation (19) and Lyapounov Law we can know that the system is stable as long as W_1 and W_2 are selected using the condition as shown in equations (17) and (18). Following from equations (17) and (18) we can get learning algorithm for the networks

$$\Delta W_1 = \xi_1 \frac{3}{2}(V_r x_1 - I_m x_3)\sigma_1$$

$$\Delta W_2 = \xi_2 \frac{3}{2} V_r x_2 \sigma_2$$

where ξ_1, ξ_2 are learning steps for the two neural networks respectively.

Note in the above neural network control strategy, an interesting character for it is that not all the weights are necessary to be updated in every training cycle because of the local weight updating scheme for B-spline neural network. In fact every time only the weight of B-spline functions that is activated need to be updated. This makes the network to be fast convergence speed and lower computation complexity. Therefore B-spline neural network is more suitable for real time applications.

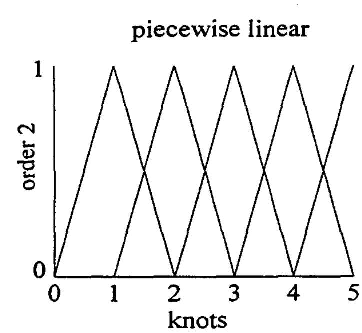

Fig.4 Univariate B-spline basis function of order 2

IV. SIMULATION RESULTS

The computer simulation of the system is based on a program written with C language. The system has been simulated for large disturbances to confirm the effectiveness of the proposed control method. The parameters of the converter are chosen as $E_m = 100$ V, $V_r = 300$ V, $\omega = 100\pi$ rad/s, $C_0 = 940\,\mu F$, $L_i = 10$ mH. Nine second-order B-spline functions are chosen for the networks and learning step for them is 0.01. In the figure 5, the simulated converter with 0.5A load current i_L is shown. It can be seen in figure 5(a) that the output of the converter is controlled to 300V. Figure 5(b) shows the unity power factor. From figure 5(b) we can find that the phase voltage and the phase current are almost in the same phase, which guarantees the unity power factor. (Note in figure 5(b) a-phase voltage is divided by a proper constant 20 in order to compare clearly with a-phase current). Figure 5(c) displays the three-phase input currents. In figure 5(d), A-phase current in one cycle and its fundamental current waveform is shown. We calculate the total harmonic distortion (THD) from it, which is 29.6% (Fourier series n is equal to 610).

Figure 6 shows the output voltage, input voltage and currents, etc., for the load current changing from 0.5A to 1A.

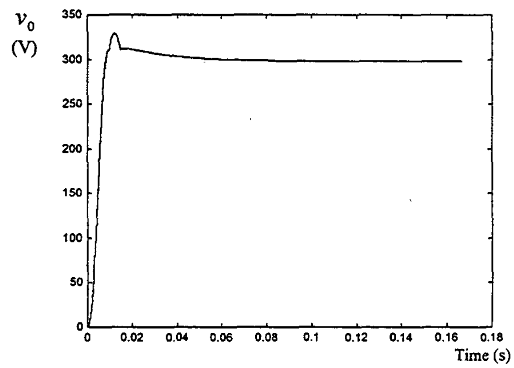

Fig.5 (a) Output voltage (i_L=0.5A)

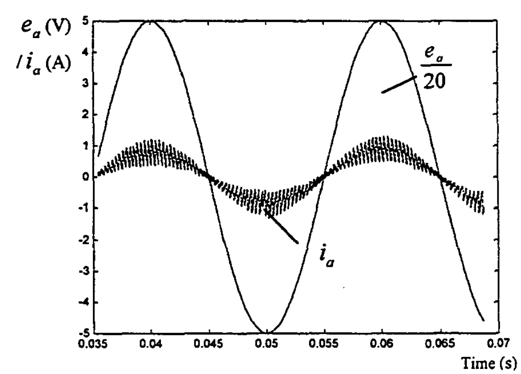

Fig. 5 (b) A-phase current and a-phase input voltage (i_L=0.5A)

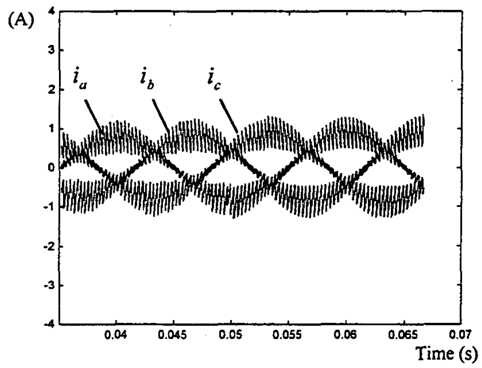

Fig.5 (c) Three-phase input currents (i_L=0.5A)

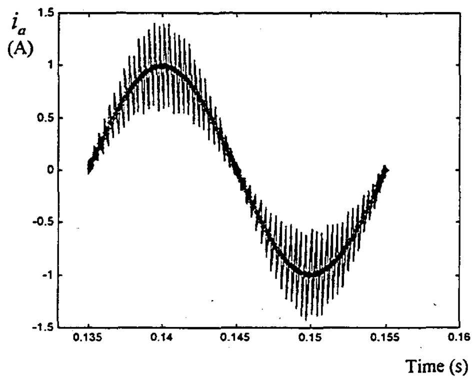

Fig.5 (c) i_a and its fundamental current waveform (i_L=0.5A, THD=0.47%)

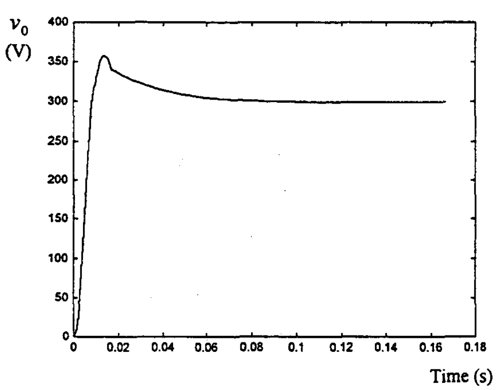

Fig.6 (a) Output voltage (i_L=1A)

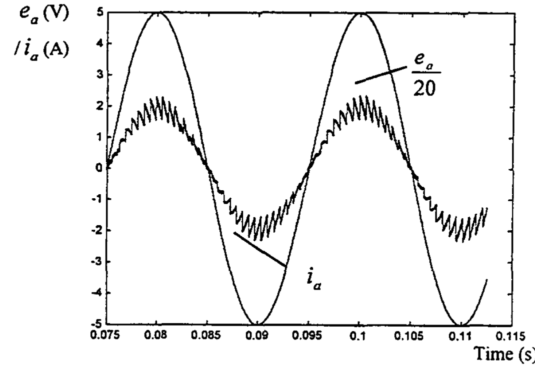

Fig.6 (b) A-phase current and a-phase input voltage (i_L=1A)

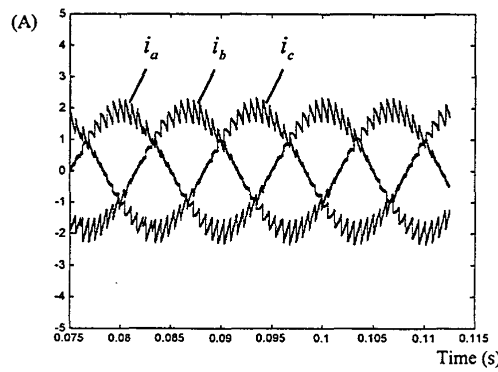

Fig.6 (c) Three-phase input currents (i_L=1A)

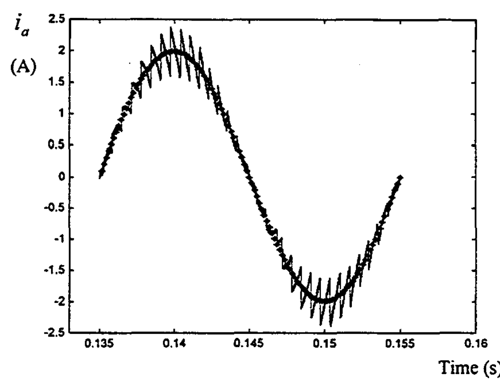

Fig.6 (d) i_a and its fundamental current waveform (i_L=1A, THD=0.81%)

We can see the system also guarantees the unity power factor and the expected output voltage. When the load current increases, the harmonics in the input sinusoidal current also increase. The total harmonic distortion calculated now is 13.4%. The distortion will decrease as the output power increase. The output power in this simulation is 150W. The final version of the system is expected to be 3kW. The THD will decrease accordingly.

V. COMPARISON WITH OTHER AC-DC CONVERTERS

The proposed system has been compared with other popular three-phase AC-DC converters. Two other systems, Current mode controlled Boost full-bridge AC-DC converter and Boost converter using modular approach [6] are considered here. The former system has the same circuit as the proposed system and is a conventional three-phase circuit. It is controlled by the conventional current-mode control in the inner loop and with a voltage mode control in the outer loop, whereas the latter system using modular approach and is consists of three single-phase circuit and each are control by voltage mode control. Their assessment is presented below:

	Adaptive B-spline Boost	Current mode controlled Boost full-bridge	Boost Modular Approach
3-phase balance	Good	Good	Fair
Low frequency harmonics	Good	Fair	Fair
Stability against circuit parameter changes	Good	Fair	Fair
Interfacing with other power converter	Good	Fair	Fair
Component count	Small	Small	Large
Future development	Easy	Fair	Fair
Maintenance	Average	Average	Easy

It can be seen that in general the adaptive B-spline method has an advantage of using advanced control method and still using the classical approach of topology. It has the advantage of good 3-phase balance because of the adaptive control method it is using. Hence the low frequency harmonics and stability are very good. The interfacing with other converter system is undertaken by using DSP control. The component count is small hence it has a better reliability. For the future development, the DSP can generate other input and output digital signals for more complex control such as modifying into a resonant circuit. The maintenance to circuitry is harder because the three circuit phases are usually in close proximity however the control parameters can be easily be changed using DSP programming, whereas the modular approach has an advantage of hardware maintenance because it consists of three exactly equal single-phase systems.

VI. CONCLUSION

The proposed adaptive B-spline network control for three-phase PWM AC-DC voltage source converter has been described and verified by computer simulation. We can see from the simulation results that the system with the proposed control method has a stable operation at various load conditions. It draws nearly sine wave current from the utility line with unity power factor.

It is a new application using neural network control for converter, so there are still many problems in practical applications. This is also our future's investigation. However we deeply believe that as a new control method neural network can be used well for converters in the future.

VII. ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the Hong Kong Polytechnic University for this project.

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