Switching Control of an AC/DC Converter by Neural Networks

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Abstract

The switching control of a bidirectional AC/DC converter by Neural Networks is proposed in this paper. With this neural network application, an AC/DC converter has advantages such as quick switching response, simpler structure and better output waveform. The converter can be modified by a PWM rectifier switching state or predictive state observer and controller such as artificial intelligence based one to avoid time-delays causing transient conditions. The obtaining method of the circuit is given. The simulation of switching conditions is shown. To confirm the approximation and the operation by detecting and reducing line harmonic currents, the theoretical results and computer simulations are given.

Keywords: AC/DC Converter, Switching Semiconductors, Neural Networks

I. Introduction

Some of the most well known problems in AC/DC converters are reducing the line harmonic currents designing the effective filter system and fast transient response. In time AC/DC converters have been dominated by uncontrolled rectifiers or line-commutated phase-controlled rectifiers. Such converters have the inherent drawback that their power factor decreases when the firing angle increases, and the lower order harmonics of line current are quite high [1],[2].

The advantages of PWM rectifiers [1], [2], [3], [4] are as follows: First, the input current can be changed to sinusoidal form which reduces the lower order line harmonics. Second, the input power factor can be controlled with the phase of input current with respect to the input voltage which can be adjusted. Third, the dc-link voltage can be regulated quickly against the variation in load. Fourth, the excess power in the load side can be regenerated into the input side. In order to realize these advantages, IGBT or thyristor switching semiconductors, current sensors, and current sensor controllers are needed. Current sensors are used to detect and control the input phase currents with the consideration of error rate. In every PWM period, currents in the circuit can be extracted from the dc-link current with a given voltage vector [5], [6]. Under operating conditions, it is needed to sample reliable dc current to extract the input currents from dc link voltage in a minimum amount of time. In order to avoid the time-delay, the converter can be modified by PWM rectifier switching state or predictive state observer and controller such as an artificial intelligence-based one.

Moreover, existing AC/DC converters draw non-sinusoidal input current. A full-wave bridge followed by a bulk capacitor which has an input current with harmonics is undesirable. To reduce harmonic currents, there are some techniques such as active filtering, passive filtering, power factor correction and/or reducing the time-delay by neural networks, [7] etc... Figure 1 shows the well-known power flow scheme of a single phase bidirectional AC/DC converter.

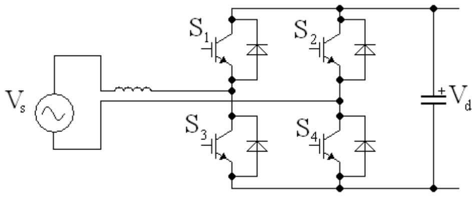

Fig. 1. Power flow scheme of a single phase bidirectional AC/DC converter.

Another problem related with existing drive systems is that the size of the dc-link capacitor is frequently very large to limit the link voltage. This capacitor both increases the size of the system and the equipment cost, and to reduce its size, a bidirectional switched mode rectifier can be used.
For a single phase system generally four control switches are used in a general bidirectional converter topology. Here, four converter IGBT and thyristor type semiconductors will be used for comparison in the case of switching conditions. An IGBT used in rectification stage has advantages such as robust and line commutation. As a switching element, thyristors has the highest catalogue values in terms of voltage and current. Furthermore the power flow of this converter has rectangular currents, and it can be applied to general industrial electronic motor drive systems [5].

The general operating principles of an IGBT is as follows: firstly it has very high input impedance; thus, it has low voltage between its terminals when it is forward biased. The magnitude of their switching frequency is lower than MOSFETs, and higher than BJT. If the current which is controllable exceeds the upper level then the switching element is locked and no more can be controlled by its gate terminal. In that case, to deactivate the switching element the load current should be less than the hold current or the direction of the voltage between collector and emitter should be changed with an outer commutation circuit.

The driving circuit of a typical IGBT is the same as MOSFET, and the linkage capacitors between an IGBT's terminals are rather low. In PWM type rectifiers, when the switching frequency increases, the power loss becomes high during the deactivation of the switching element and the commutation diode. This case limits the usage of an IGBT with 50 kHz as the switching element.

Thus, in high frequency resonance-type inverters, it can be practically used at the frequency of 250 kHz. For 50 kHz, the power loss during conduction of an IGBT is approximately 6 watts. For 250 kHz it is approximately 0.8 watts.

A thyristor (SCR) is the most common used element in power electronics. SCR is a switching element which can be triggered easily at high temperature or high voltage. For high current or voltage thyristors it is not easy to deactivate the element without a commutation circuit. Because of the dead time and the high power dissipation during conduction, they can not be used at high frequency applications. The switching frequency in which they are generally used is approximately 5 kHz.

The switching frequency ratings of an IGBT are higher and its switching power loss is lower than SCR. It can easily be triggered compared to SCR. However its conduction voltage and conduction power loss between its terminals is more than SCR. Thus, for the maximum current and voltage ratings conventional SCR has the advantage (5000V, 5000A) [8].

II. Fundamentals of the subject

The proposed high power factor AC/DC bidirectional converter consists of three components:

- Power conversion stage
- Inductor average current controller
- Synchronization circuit to trigger the switching elements (IGBT or thyristors).

The power conversion stage contains four switching elements (IGBT or thyristor); two fully controlled switches (S_1, S_2), two diodes (D_1, D_2), one inductor (L) and finally one capacitor (C).
The operating mode of the converter is accomplished by S_2 (either switched off in powering mode or turned on in regenerating mode), and determined by the DC voltage V_{dc}. The converter works initially in the powering mode. For motoring operation, the converter works as a boost converter and S_2 is kept in blocking mode. For regeneration S_2 is switched on and the converter is used as a buck converter.

Here, for this converter, isolated gate drives synchronize the switching operations of rectifying switching elements with the line voltage. Figure 2 shows the motoring and regenerating timing diagrams, and the operation of motoring [1], respectively.

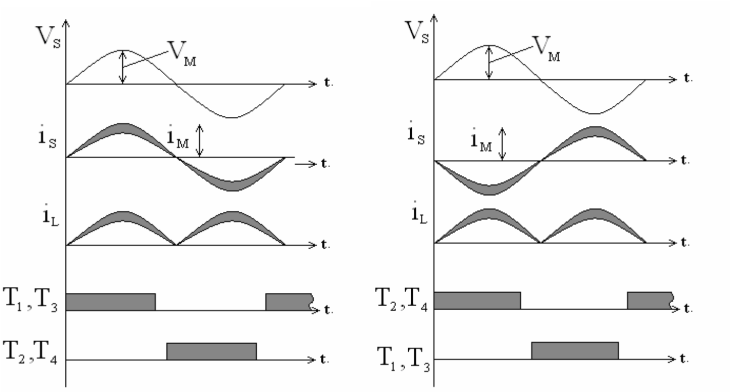

Fig. 2. Timing diagrams of motoring mode and regenerating mode respectively.

III. Analyzing the operating conditions

A. Analyzing the operation of motoring

For the motoring operation T_1–T_4 are obliged to synchronize with the line voltage v_S by the isolated gate drives and modeled by neural networks. At this time, S_2 is switched off for the period of the motoring cycle and D_2 is forward biased while T_1–T_3 is switched on in the positive half cycle of v_S, while T_2–T_4 are switched on in the negative half cycle. The timing diagram of the ripple current in a duty cycle of S_1 is seen in Figure 3. The inductor current is manipulated to follow the rectified waveform of v_S by a current modecontrolled PWM signal. The feedback current i_{fb} which is compared with the reference waveform i_{ref} is forced to oscillate between the maximum and the minimum values of i_{ref}. This can be seen in the second part of Figure 3.

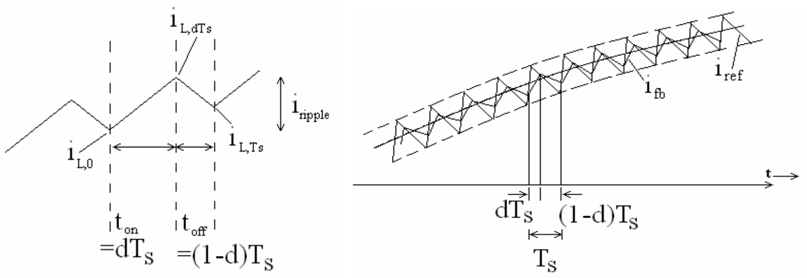

Fig.3. Timing diagrams of ripple current i_{ripple} for a dT_S amount of time interval (d is the duty cycle of S_1), and Waveforms of feedback and reference current respectively.

$$i_{L(NN)}(t) = i_{L,dTs} + \frac{v_S - |i_{ref} - i_{out}|R_L}{L}t \tag{1}$$

$$i_{L(NN)}(t) = i_{L,0} + \frac{v_S dT_S}{L} + \frac{v_S - |i_{ref} - i_{out}|R_L}{L}t$$

at the end of the cycle,

$$i_{L,Ts} = i_{L,0} + \frac{v_S}{L}T_S - \frac{|i_{ref} - i_{out}|R_L}{L}(1-d)T_S \tag{2}$$

here, *(1–dT*$_S$*)* refers to run time interval. The quasi steady–state conversion characteristic is,

$$|v_S| = |i_{ref} - i_{out}|R_L(1-d) \tag{3}$$

as,

$$|v_S| = v_m|\sin wt|; d(t) = 1 - \frac{v_m}{|i_{ref} - i_{out}|R_L}(\sin wt) = 1 - \frac{1}{M_1}|\sin wt| \tag{4}$$

B. *Analyzing operation of regenerating*

Contrary to the motoring mode switch S_2 is turned on and the polarity of D_2 is reversely biased. For that matter the converter acts as a buck converter with an input voltage of bulk capacitor. T_2 and T_4 are turned on in the positive half cycle while T_1, T_3 are turned on in the negative half cycle.

The operation continues very simply since it is achieved by triggering the select switch in Figure 4 to divert the signals applied T_1–T_4. The semiconductors used in the power stage are naturally commutated. Therefore, there is no need to use an extra commutation circuit for turned on–off operations. In regenerating mode the inductor current flows in the same direction as in motoring mode. Therefore, it can easily be seen that the two operating modes have the same current profile. In this operating mode, the first is operating for a time interval of $t_{on} = dT_S$ (d is the duty cycle of S_1) and the second topology is operating for a time interval of $t_{off} = (1–dT_S)$.

In one switching cycle, i_L can be define with its initial value $i_{L,0}$ as

$$i_L(t) = i_{L,0} + \frac{|i_{ref} - i_{out}|R_L - v_S}{L}t \tag{5}$$

at the end of the on time of S_1, i_L is,

$$i_{L,dTs} = i_L\left(dT_S\right) = i_{L,0} + \frac{\left|i_{ref} - i_{out}\right| R_L - v_S}{L} dT_S \qquad \textbf{(6)}$$

i_L can be defined as,

$$i_L\left(t\right) = i_{L,dTs} - \frac{v_S}{L} t \qquad \textbf{(7)}$$

this stage is also called $t_{off} = (1–d)T_S$. Nevertheless,

$$i_{L,dTs} = i_L\left[\left(1-d\right)T_S\right] = i_{L,0} + \frac{\left|i_{ref} - i_{out}\right| R_L - v_S}{L} dT_S - \frac{v_S}{L}\left(1-d\right)T_S \qquad \textbf{(8)}$$

this time, the quasi steady–state conversion can be applied as,

$$\left|V_S\right| = d\left|i_{ref} - i_{out}\right| R_L \;\; ; \;\; \left|V_S\right| = V_m \left|\sin wt\right| \qquad \textbf{(9)}$$

$$d = \frac{V_m}{\left|i_{ref} - i_{out}\right| R_L}\left|\sin wt\right| = \frac{1}{M_2}\left|\sin wt\right|$$

C. *Designing L*

As clarified before i_{ripple} which flows through the inductor is,

$$\begin{aligned} i_{ripple} &= \frac{\left(\left|i_{ref} - i_{out}\right| R_L - v_S\right)}{L} dT_S \qquad \textbf{(10)} \\ i_{ripple} &= \frac{\left(\left|i_{ref} - i_{out}\right| R_L - v_m\left|\sin wt\right| d\left|\sin wt\right|\right)}{L} T_S \\ i_{ripple} &= \frac{\left|i_{ref} - i_{out}\right| R_L T_S}{L}\left(1 - \frac{1}{M_2}\left|\sin wt\right|\right)\frac{1}{M_2}\left|\sin wt\right| \\ &\Rightarrow \frac{V_m T_S}{L}\left|\sin wt\right|\left(1 - \frac{1}{M_2}\left|\sin wt\right|\right) \end{aligned}$$

The minimum inductor value L_{min} that limits the maximum ripple current to a value $i_{ripple,,max}$ is;

$$L_{min} = \frac{V_m M_2 T_S}{4 i_{ripple,max}} \qquad \textbf{(11)}$$

For all equations, the output voltage is taken as constant. S_2, the choice of a semi-controlled switch such as a thyristor or a fully-controlled switch like IGBT depends on the maximum voltage ripple allowed in the dc link capacitor. When there is a mode change from regeneration to motoring, the “boost” converter must increase the dc link capacitor voltage above the peak value of the line voltage before line current shaping becomes effective. If this voltage fluctuation is to be kept small, then, it is better to use a fully controlled switch for S_2 [1].

IV. The operation condition of neural network

The network receives the phase current error signals through the scaling gain K and generates the PWM logic signals for driving the converter main current devices. The sigmoid function is clamped to 0 or 1 when the threshold value is reached. The output signals have four possible states corresponding to four states of the converter switching conditions. If the current in a phase reaches the threshold value +0.01 the respective output should be 1 which will turn on the upper device of the leg. If, on the other hand, the error reaches –0.01, the output should be 0 and the lower device will be switched on. The network is trained with four input-output patterns in tables 1 and 2. The classic back propagation (CBA) algorithm is used to train the switching conditions of semiconductor elements [8], [9]. It is given the ON/OFF states of switching elements for training and test phase applications of NN in tables 1 and 3 respectively, and Figures 4 and 5 show the simulation circuit and the switching results of semiconductor elements in the NN test phase. The variations of input currents i_S and i_L without the NN controller are depicted in Figure 6. In this figure, it can be seen that without the NN controller, the converter draws an unstable current from the main supply. Because the time delays occurred in the semiconductor's triggering, the current waveforms are not smooth. Figure 7 shows the input current i_S on which the harmonics on the main supply are reduced, the approximated sinus current curve is maintained and the inductor current i_L on which there is no affection of inrush current as well. The advantageous of the NN controller are as follows: First, The switching frequency increases significantly. Second, the increase in switching frequency speeds up the switching element's turn on and off operations. In this way, the effect of harmonics and disturbances is minimized. Thus, the control of power flow is done with the help of the NN controller, and the energy conserved in capacitor is transmitted to the main supply.

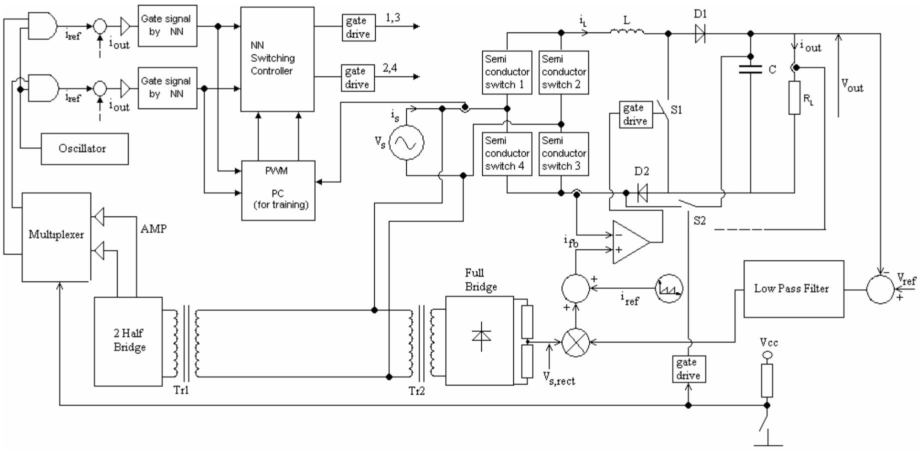

Fig. 4. Simulation circuit, test the performance of the switching elements.

Table 1. The values of ON/OFF states used in the training phase of the NN switching controller for IGBT.

i_f	i_n	T_1	T_2	T_3	T_4
0	0	0	0	0	0
0.01	-0.01	1	0	1	0
-0.01	0.01	0	1	0	1
1 (0)	1 (0)	0	0	0	0

Table 2. The values of ON/OFF states used in the training phase of the NN switching controller for Thyristor.

i_f	i_n	T_1	T_2	T_3	T_4
0	0	0	0	0	0
0.01	-0.01	1	0	1	0

-0.01	0.01	0	1	0	1
1 (0)	1 (0)	0	0	0	0

Table 3. The NN test phase result for one of four switching conditions for switching elements.

	i_f	i_n	T_1	T_2	T_3	T_4
SCR	0.01	-0.01	0.99655	0.00142	0.99762	0.00007
IGBT	0.01	-0.01	0.99785	0.00127	0.99833	0.00005

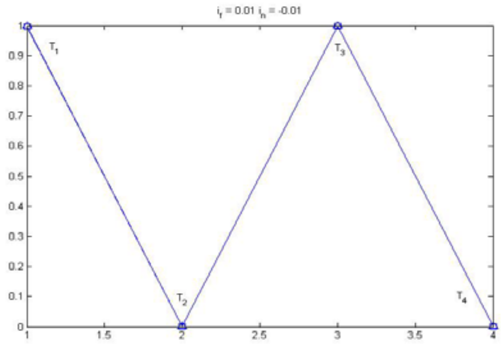

Fig.5. ON/OFF test phase results of the Neural Network (NN) controller

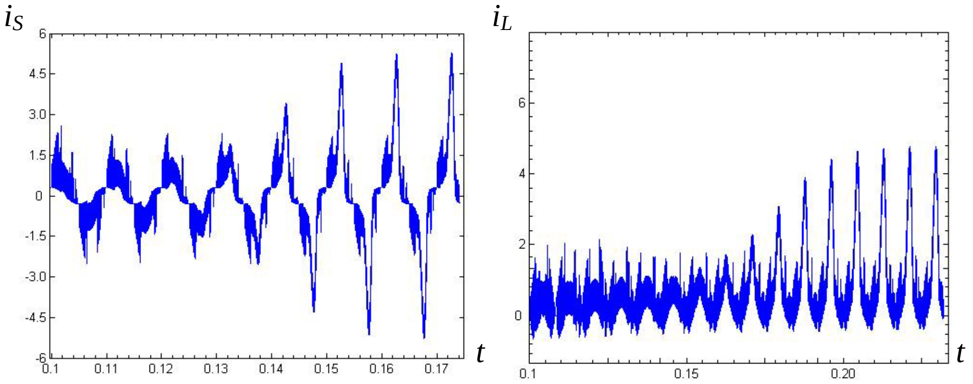

Fig. 6. The variation of the input current i_S, and the variation of the input current i_L, are both examined in the MATLAB-Simulink simulation environment (without the NN controller).

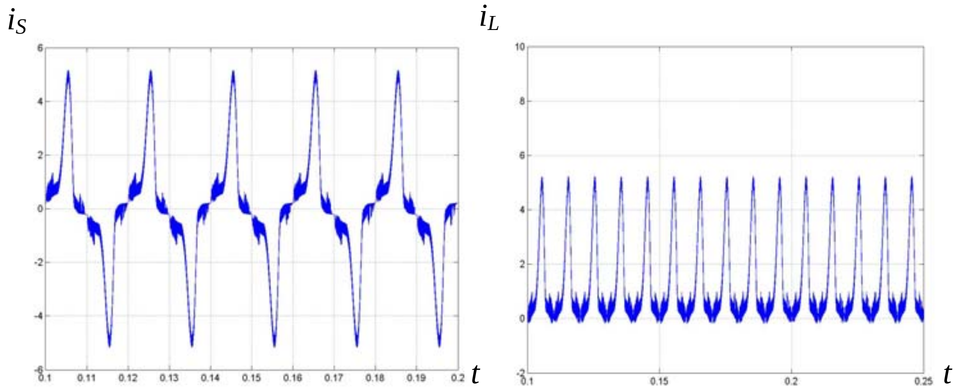

Fig. 7. The variation of the input current i_S, and variation of the input current i_L (with the NN controller).

V. Conclusions

The switching control of an AC/DC converter for different switching elements which are IGBT and thyristor for time delays of transient conditions has been applied and analyzed. From the results, it is understood that time delays are minimized, switching frequency is increased and the switching elements -thyristor, IGBT- are turned on and off in high speed by the NN controller.
In this way, in the structure of the converter, the size of the dc link capacitor can be reduced because of the bidirectional power flow capability and the energy storage requirement. The system reduces harmonic pollution of ac drives because of bidirectional power flow conditions with unity power factor. It works with IGBT or thyristor-type phase-controlled rectifiers, which are robust and line commutated.

For the reliable input currents two methods were proposed. One was the method of modifying the switching state of the PWM rectifier and the other one was the predictive state observer, that is neural network based switching to main components of IGBTs or thyristors to prevent time-delays.

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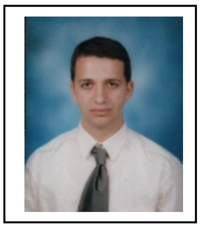

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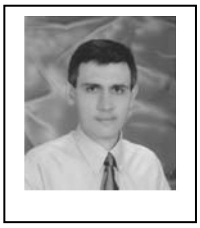

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