DSP microcontroller-based fuzzy control of a DC/DC parallel resonant converter using phase-shift PWM technique

İres İskender
Electrical and Electronics Engineering Department, Gazi University, Ankara, Turkey, and
Yıldırım Üçtuğ and H.Bülent Ertan
Electrical and Electronics Engineering Department, Middle East Technical University, Ankara, Turkey

Received February 2003
Revised April 2006
Accepted April 2006

Abstract

Purpose – To analyze the operating performance of an ac-dc-ac-dc PWM parallel resonant converter operating at lagging power factor mode controlled based on fuzzy logic control method.

Design/methodology/approach – A range of published works relevant to dc-ac-dc converters and their control methods based on PWM technique are evaluated and their limitations in converter output voltage control are indicated in the first section of this paper. The Simulink model and different stages of the converter are described in the second section. In Section 3, the general mathematical model of the system is derived and the phase-shift PWM switching technique is explained. The equivalent circuit of the high-voltage high-frequency transformer used in the converter and the effects of the transformer parameters on the converter operation are presented in Section 4. In Section 5, fuzzy logic control and the basic concepts of this method are described and its application to the proposed converter output voltage control is explained. In Section 6, the Simulink simulation results of the fuzzy logic control application are given for different operating conditions. In Section 7, an overview of the hardware used in this study is presented and the experimental results are given to show the performance of the controller. Finally, Section 8 gives the conclusions of the study.

Findings – The fuzzy logic control which is a suitable method for nonlinear systems such as the converter proposed in this paper, is successfully applied for output voltage control of the converter. The controller performance is satisfied. The phase-shift angle of the converter is used as the control parameter. The paper also presents how the parasitic parameters of the transformer used in high-voltage applications can be used as the circuit resonant elements.

Research limitations/implications – In preparing this paper, the resources books and periodic journals existing in our university library and also the English resources relative to dc-ac-dc converters reachable through the internet were researched.

Practical implications – The suggested control method can be used in the control of linear and nonlinear systems. The study carried out in this paper is also a very good approach to be used in high-voltage high-frequency converters output voltage control.

Originality/value – Since, the control approach proposed in this paper does not require the information on converter and transformer parameters that affect the converter output voltage, so it can effectively be used in applications where there are parameter variation problems. The design of the transformer for the required load, finding an optimum operating frequency for the converter, and using the transformer parameters as resonant elements of the circuit to decrease the switching losses are the other contributions of this paper.

Keywords High voltage, Transformers, Fuzzy control

Paper type Research paper

COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering
Vol. 25 No. 4, 2006
pp. 827-840

0332-1649
DOI 10.1108/03321640610684024

1. Introduction

There are many dc-dc power conversion applications where the input voltage has to be converted into a high output voltage. To increase the output voltage to the required load voltage level a high-ratio transformer is used at the output of the inverter. The non-linearities of the high-voltage transformer are used as the resonance elements of the resonant circuit. The operation of the system at resonance and lagging power factor mode has many advantages, which are well documented in (Bhat and Swamy, 1989; 1990).

For the medical diagnostic use, a low ripple tube voltage waveform with fast rising time is required which is obtained by increasing the operating frequency of the inverter to resonance frequency. Increasing the operating frequency also reduces the volume and weight of the high-voltage transformer.

Owing to wide adjustment range of the load, the phase-shift pulse width modulation method is used to control the tube voltage; by varying the phase-shift angle of the inverter from 180° to zero, the tube voltage changes from zero to its maximum value. The output voltage regulation is achieved by using feedback control method by having feedback from the tube voltage.

There is a complex relationship between the output voltage and the phase-shift angle. For controlling such a complicated system a classical control method can be used, but with a number of simplifying assumptions or by designing a very complex control algorithm which requires powerful computing, fast and precise data acquisition equipment.

Designing a conventional controller presents problems since modeling the system is very difficult due to its non-linearity. However, fuzzy technique, which has gained popularity in recent years, looks very promising for this application. The design of the fuzzy controller together with the MATLAB/SIMULINK simulation and experimental results are described in this paper. The results show how well this controller eliminates the 100 Hz ripple at the output and provides a very fast rise time. The mathematical simulation and the experimental results have been obtained by employing the fuzzy control method.

2. Description of the converter circuit

Figure 1 shows the simulink model of the system. The first stage of the converter is an uncontrolled rectifier connected to the ac mains through an inductor representing the ac line inductance (L_1). The ac mains supply is considered to be 220 V (rms) at a

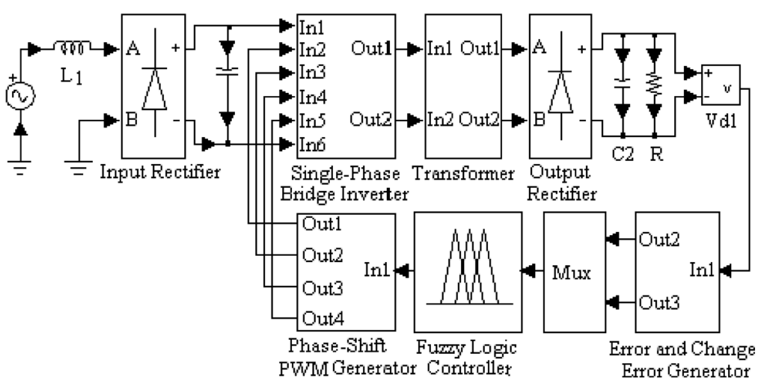


Figure 1.
Simulink model of the converter

frequency of 50 Hz. The mean value of the dc link voltage (v_{C0}) depends on both the load current and the ac line inductance. The dc link voltage has a ripple with frequency twice that of the ac mains supply.

The inverter used in both software simulation and experiments is a single-phase bridge operating around the resonant frequency of the system (lagging mode) so that the switching lossless of the transistors are considerably reduced (Vandelac and Ziogas, 1988). The high-voltage transformer was designed to have a minimum volume satisfying the load with specifications of 125 kV and 100 mA (X-ray tube equivalent circuit). The non-linearities of the high-voltage transformer used in parallel resonant converter are incorporated in basic converter operation, rather than as parasitic elements that interfere with basic operation of the converter. The winding capacitance of the transformer is used as the resonant capacitor so that the external tank capacitor is completely eliminated and the leakage inductance of the transformer constitutes the resonant inductance. The voltage at the secondary of the high frequency transformer is once more rectified and applied to the X-ray tube. The tube voltage is controlled by phase-shift PWM of the power semiconductor switches. A software was developed for designing the transformer to achieve desired lumped parameters, while minimizing the volume. An investigation is carried out to determine optimum operating frequency of the transformer. The parameters obtained in transformer design are used in both analytical simulation and laboratory experiments.

3. Mathematical model

The general mathematical model of the system is obtained by deriving and combining the mathematical models of the ac-to-dc and dc-to-dc converters. The model obtained is used to study the steady-state and transient performance of the system.

3.1 Input rectifier

The steady-state and transient behavior of the uncontrolled input rectifier can be described in three sub-modes as shown in Figure 2.

The following equations can be written for the above operating modes.

Mode 1: D_1, D_4 are turned on and the capacitor C_0 is charging:

$$v_1 = L_1(\mathrm{d}i/\mathrm{d}t) + v_{C0} \quad C_0(\mathrm{d}v_{C0}/\mathrm{d}t) = i_1 - i_2 \quad v_{ab} = v_{C0} \quad i = i_1 \tag{1}$$

Mode 2: D_2, D_3 are turned on and the capacitor C_0 is charging:

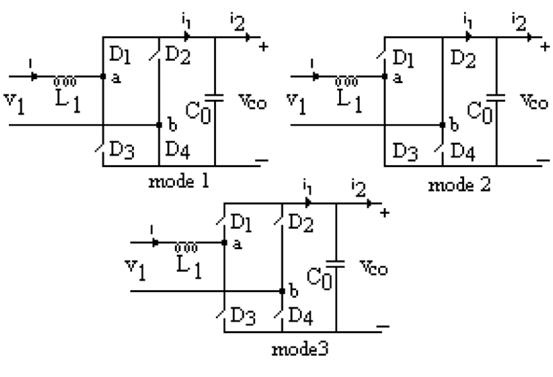


Figure 2. Equivalent circuit of the input rectifier for different operating modes

$$v_1 = L_1(\mathrm{d}i/\mathrm{d}t) - v_{C0} \quad C_0(\mathrm{d}v_{C0}/\mathrm{d}t) = i_1 - i_2 \quad v_{ab} = -v_{C0} \quad i = -i_1 \tag{2}$$

Mode 3: D_1, D_2, D_3, D_4 are turned off and the capacitor C_0 is discharging. In this mode the load is disconnected from the ac mains:

$$v_1 = v_{ab} \quad C_0(\mathrm{d}v_{C0}/\mathrm{d}t) = -i_2 \quad i = i_1 = 0 \tag{3}$$

3.2 DC-DC converter model

Figure 3 shows the second part of the converter including inverter, transformer and the output rectifier. The equivalent circuit of the high-voltage transformer is shown by L_t, r_t and C_t corresponding to leakage inductance, winding resistance and winding capacitance of the transformer, respectively. The equivalent circuit of the converter depends on the on-off conditions of the inverter switches. The output dc voltage of the converter is controlled using phase-shift PWM control method (Sun *et al.*, 1996). In this method the first leg switches (S_1, S_2) operate alternatively out of phase as reference switches and the second leg switches (S_3, S_4) also operate in the same manner, but with a phase-shift angle (Φ) with respect to the first leg switches. By varying the phase-shift angle from 180° to 0 the output dc voltage can be changed from zero to its peak value continuously. The symmetrical output voltage waveforms of the inverter are shown in Figure 4 for 0 and $\pi/3$ rad phase-shift angles.

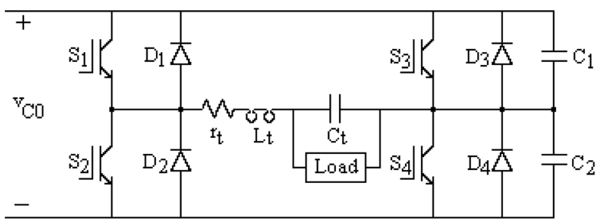
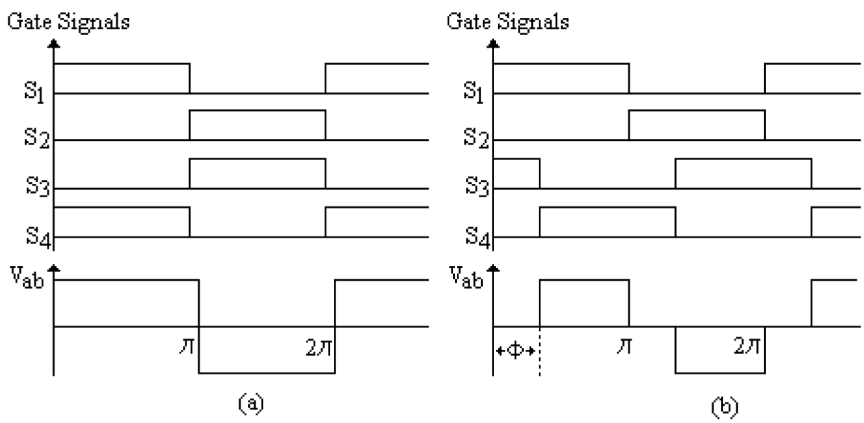


Figure 3.
Circuit diagram of the full bridge resonant inverter



Notes: (a) phase-shift angle is zero (b) phase-shift angle is π/3 rad

Figure 4.
Switching sequence in phase-shift PWM control method

The voltage at the primary side of the transformer, which has a square waveform is stepped-up by the transformer and then rectified to feed the X-ray tube through the high-voltage cable. The capacitance of the X-ray cable is utilized as smoothing capacitor.

There are 12 operating modes according to on-off conditions of the inverter switches. Owing to the symmetry of the input voltage, the circuit behavior can be described in six sub-modes as shown in Figure 5.

The following assumptions are made in deriving the analytical model of the dc-dc converter.

- switching devices, the inductor and the capacitors in the equivalent circuit of the converter are assumed to be ideal with no losses;
- wiring inductance and resistance are neglected;
- the X-ray tube is represented by a resistance corresponding to the ratio of the tube voltage to its current; and
- the load resistance and smoothing capacitance in the secondary side of transformer are referred to the primary side according to the transformer turns ratio.

The state equations corresponding to the circuit operation modes in Figure 5 can be written as:

Mode 1:

$$\mathrm{d}/\mathrm{d}t\begin{bmatrix} i_{\mathrm{t}} \\ v_{C\mathrm{t}} \\ v_{C2} \end{bmatrix} = \begin{bmatrix} -r_{\mathrm{t}}/L_{\mathrm{t}} & -1/L_{\mathrm{t}} & 0 \\ 1/C_{\mathrm{t}} & 0 & 0 \\ 0 & 0 & -1/R_L C_2 \end{bmatrix}\begin{bmatrix} i_{\mathrm{t}} \\ v_{C\mathrm{t}} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} v_{C0}/L_{\mathrm{t}} \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

Mode 2:

$$\mathrm{d}/\mathrm{d}t\begin{bmatrix} i_{\mathrm{t}} \\ v_{C\mathrm{t}} \end{bmatrix} = \begin{bmatrix} -r_{\mathrm{t}}/L_{\mathrm{t}} & -1/L_{\mathrm{t}} \\ 1/C & -1/R_L C \end{bmatrix}\begin{bmatrix} i_{\mathrm{t}} \\ v_{C\mathrm{t}} \end{bmatrix} + \begin{bmatrix} v_{C0}/L_{\mathrm{t}} \\ 0 \end{bmatrix} \quad v_{C2} = v_{C\mathrm{t}}, \quad C = C_{\mathrm{t}} + C_2 \tag{5}$$

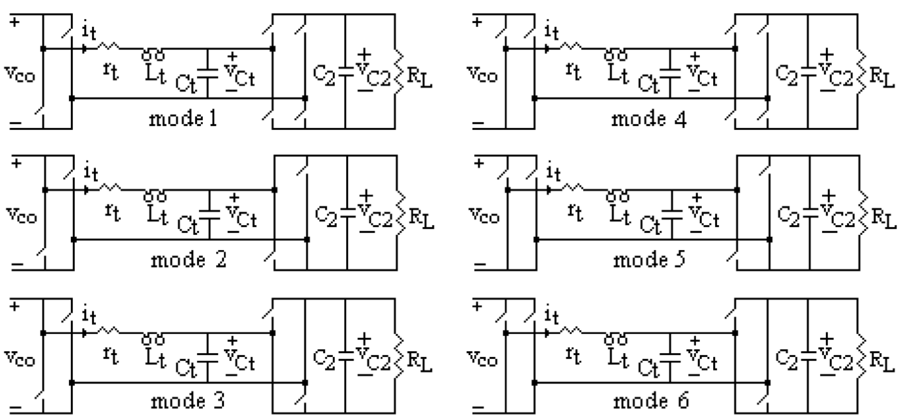


Figure 5.
Equivalent circuits of dc-dc converter for different operating modes

Mode 3:

$$d/dt\begin{bmatrix} i_t \\ v_{Ct} \end{bmatrix} = \begin{bmatrix} -r_t/L_t & -1/L_t \\ 1/C & -1/R_L C \end{bmatrix}\begin{bmatrix} i_t \\ v_{Ct} \end{bmatrix} + \begin{bmatrix} v_{C0}/L_t \\ 0 \end{bmatrix} \quad v_{C2} = -v_{Ct}, \quad C = C_t + C_2 \tag{6}$$

Mode 4:

$$\mathrm{d}/\mathrm{d}t\begin{bmatrix} i_t \\ v_{Ct} \\ v_{C2} \end{bmatrix} = \begin{bmatrix} -r_t/L_t & -1/L_t & 0 \\ 1/C_t & 0 & 0 \\ 0 & 0 & -1/R_L C_2 \end{bmatrix}\begin{bmatrix} i_t \\ v_{Ct} \\ v_{C2} \end{bmatrix} \tag{7}$$

Mode 5:

$$\mathrm{d}/\mathrm{d}t\begin{bmatrix} i_t \\ v_{Ct} \end{bmatrix} = \begin{bmatrix} -r_t/L_t & -1/L_t \\ 1/C & -1/R_L C \end{bmatrix}\begin{bmatrix} i_t \\ v_{Ct} \end{bmatrix} + \begin{bmatrix} v_{C0}/L_t \\ 0 \end{bmatrix} \quad v_{C2} = v_{Ct}, \quad C = C_t + C_2 \tag{8}$$

Mode 6:

$$\mathrm{d}/\mathrm{d}t\begin{bmatrix} i_t \\ v_{Ct} \end{bmatrix} = \begin{bmatrix} -r_t/L_t & -1/L_t \\ 1/C & -1/R_L C \end{bmatrix}\begin{bmatrix} i_t \\ v_{Ct} \end{bmatrix} + \begin{bmatrix} v_{C0}/L_t \\ 0 \end{bmatrix} \quad v_{C2} = -v_{Ct}, \quad C = C_t + C_2 \tag{9}$$

The state equations corresponding to the second half cycle of the inverter voltage are the same as those for the operating modes 1-6 with the only difference in the polarity of v_{C0}.

4. Transformer

Owing to the requirement of high-voltage output the turns-ratio of the transformer must be high, which increases the parasitic circuit parameters of high-voltage high-frequency transformer. The insulation thickness between the secondary and primary windings and also between the windings and the core strongly depends on the voltage ratings of the transformer. The need for a sufficient isolated distance between the primary and the secondary windings, which is practically required to obtain the effective allowable insulation voltage, increases the parasitic leakage inductance. The value of leakage inductance depends on the dimensions of the transformer and is independent of transformer core material (Mclyman, 1978).

When the operating frequency increases the effect of the winding capacitances becomes important and they should be considered in deriving the equivalent circuit of the transformer. It is difficult to express all the existing capacitances in a single equation, but those which are important can be written as:

- winding-to-core capacitance;
- winding-to-winding capacitance;
- turn-to-turn capacitance; and
- layer-to-layer capacitance.

For a high-voltage transformer the first three capacitances can be neglected since they are very small with respect to the fourth one (Hino, 1989; Mclyman, 1978). The secondary-side layer-to-layer capacitance, which is referred to the primary-side by multiplying with the square of the large turns-ratio is not negligible. Figure 6 shows the equivalent circuit of the high-voltage high-frequency transformer, the parameters of which were used in this study (Mclyman, 1978; Grossner, 1967).

In Figure 6, r_t, L_t and C_t are the winding resistance, leakage inductance and secondary layers capacitance of the high-voltage high-frequency transformer referred to the primary side.

The leakage inductance and the winding capacitance can significantly change the converter behavior. In switched-mode converters the leakage inductance causes undesirable voltage spikes which can damage circuit components and the winding capacitance results in current spikes and slow rise times.

A UI-type ferrite core was considered in the transformer design. The coils are wound on one leg such that the primary coil is wound on the core and the secondary coil on top of the primary coil. The transformer was designed to have a minimum volume while satisfying the converter specifications and operating near its resonant frequency. The operating point is affected by L (transformer leakage inductance + external inductance if needed), C_t and n (turns ratio of the transformer) which should be chosen such that the current flowing through transformer primary and switches is at a minimum. For design purpose, the input voltage of the transformer is idealized and taken as a square waveform. Then taking into consideration the circuit equations, transformer parameters and their relations with transformer dimensions, power losses of the transformer and its efficiency, heating and cooling conditions and magnetic conditions given in Eskandarzadeh (1996), an optimization problem was written to minimize the transformer volume using the minimization program, GRG2 (Lasdon and Waren, 1989).

The volume of the transformer has been considered as a cubical volume covering the transformer. The results indicated that, for a ferrite core, the volume is minimized around 15 kHz and no further reduction in volume is achieved by further increasing the operating frequency. The referred values of the transformer equivalent circuit components obtained from the minimization program are given below:

Turns ratio = 600

Leakage inductance = 20.34 μH

The secondary layers capacitance = 2.566 μF

Optimal operating frequency = 15 kHz

Transformer volume = 7,480 cm^3

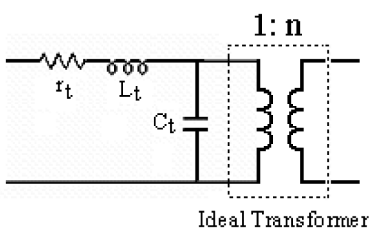


Figure 6. Equivalent circuit of a high-frequency high-voltage transformer

5. Output voltage control

The purpose of the tube voltage control is to keep constant the output voltage of the converter at the set value by varying the phase-shift angle of the inverter. The maximum (V_{max}) and minimum values of tube voltage are obtained for α (phase-shift angle) corresponding to 0 and 180°, respectively.

The system shown in Figure 1 is non-linear due to the existence of uncontrolled rectifiers at the input and output, and therefore, necessary conditions are not satisfied for the study of the converter from the viewpoint of controllability and observability. Fuzzy control method does not need accurate mathematical model of a plant, and therefore, it suits well to a process where the model is unknown or ill-defined (Mattaveli *et al.*, 1997; Bose, 2002). Even when the plant model is known, there may be parameter variation problem. In general, fuzzy expert system is applicable wherever the knowledge base of expert system contains fuzziness. In this study, fuzzy control method has been used and the basic concepts of fuzzy control are explained.

A fuzzy logic controller may consist of three basic blocks, namely fuzzification, inference system and defuzzification. The fuzzification of the input variables is the first step of the fuzzy control and is a procedure to process the input variables with membership functions (MFs) and determine the degree with which the input variables are belonging to each of the appropriate fuzzy sets via MFs. MFs are used to convert each of input variables into membership value between 0 and 1.

The overall performance of the system is affected by the shapes and number of the MFs that are chosen according to the experience of expert people about the process. Just as there are an infinite number of ways to characterize fuzziness, there are an infinite number of ways to graphically depict the MFs that describe fuzziness. Therefore, MFs may take any arbitrary shape or form, such as triangular functions, sigmoidal curves, Gaussian distribution curves, trapezoidal functions, exponential shapes or tables. There are a number of procedures given in Ross (1995) that can be used to build MFs. In this study, triangular MFs have been used as they are easier to implement and quicker to process.

In the proposed fuzzy system, there are seven fuzzy sets for each input whereas there are eleven fuzzy sets for the output. The fuzzy sets used in this study are as follows:

NVB negative very big

NB negative big

NM negative medium

NS negative small

NVS negative very small

Z zero

PVB positive very big

PB positive big

PM positive medium

PS positive small

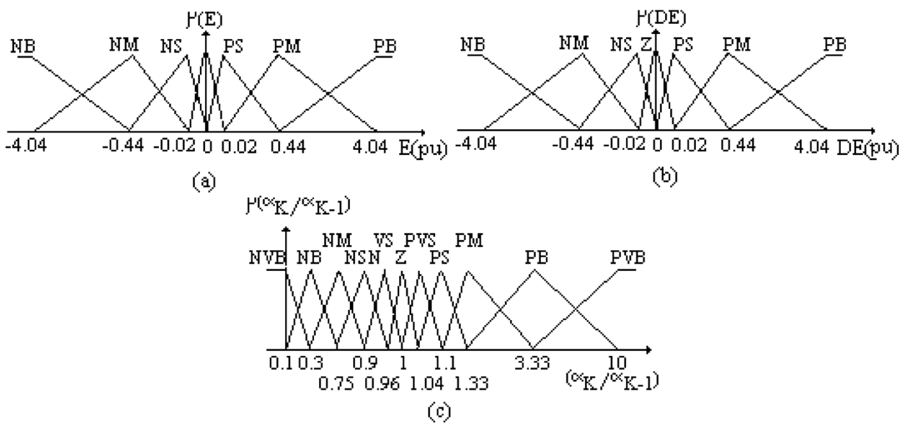
PVS positive very small

Figure 7 shows the MF plots of the variables E (tube voltage error), DE (derivative error or rate of change of error) and the phase-shift angle. The sensitivity of a variable determines the number of fuzzy subsets, respectively. Before fuzzification, the input variables are normalized with respect to reference voltage, V_{ref}. This gives the system an adaptive characteristic and enables the optimal operating point to be found effectively. The values of the MF boundaries which are in per unit have been chosen considering the characteristics of the converter. For example, the boundaries of the small fuzzy set are 0 and 0.02, which covers all the errors and derivative errors with value less than 2 percent of the reference value.

The fuzzy inference includes the process of fuzzy logic operation, fuzzy rule implication and aggregation. In the fuzzy inference system, the fuzzified input variables are processed with fuzzy operators and the IF-THEN rule implementation. The two of 49 rules of Table I are:

(1) IF error is NM AND change in error is NS THEN output is PM
(2) IF error is NM AND change in error is Z THEN output is PS

There are a number of fuzzy reasoning methods in the literature, which can be used to obtain the inference result from a system. Those are Mamdani's, Larsen's, Sugeno's



Notes: (a) Output voltage error (b) Output voltage derivative error (c) Phase-shift angle (α_K/α_{K-1})

Figure 7. MFs

Table I. Rule base table for converter output voltage controller

Error derivative	NB	NM	NS	Error Z	PS	PM	PB
NB	PVB	PVB	PB	PM	PS	PVS	NC
NM	PVB	PB	PM	PS	PVS	NC	NVS
NS	PB	PM	PS	PVS	NC	NVS	NS
Z	PM	PS	PVS	NC	NVS	NS	NM
PS	PS	PVS	NC	NVS	NS	NM	NB
PM	PVS	NC	NVS	NS	NM	NB	NVB
PB	NC	NVS	NS	NM	NB	NVB	NVB

and Tsukamoto's methods (Patyra, 1996). The Mamdani's fuzzy reasoning strategy which is the most commonly and frequently used method has been employed in this study. The fuzzy reasoning strategy of this method is based-on the MAX-MIN or (SUP-MIN) composition. Mamdani's fuzzy reasoning is shown in Figure 8.

Table I shows the corresponding rule table for the output voltage controller. The top row and left column of the matrix indicate the fuzzy sets of the variables (E and DE), and the MFs of the output variable are shown in the body of the matrix. The proposed system has 49 rules that are built by crossing the fuzzy sets considered for each input.

Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. The input of the aggregation process is the list of output fuzzy sets and the output of the aggregation process is one fuzzy set for output. In the Mamdani's fuzzy reasoning strategy used in this study, the maximum aggregate method has been used. The output of this step of FLC is a single fuzzy set obtained from the union (OR) of all the component MFs.

Defuzzification is the last step of FLC. The input for the defuzzification process is a fuzzy set obtained from the aggregation process and the output is a single value. Conversion of this fuzzy output to a crisp output is defined as defuzzification. There are a number of strategies in the literature, which can be used for performing the defuzzification. Unfortunately, there is no systematic procedure for choosing a defuzzification strategy (Chin-Teng and Lee, 1996).

Some important methods of defuzzification are:

Center-of-area (COA) method, which determines the center of the area of the combined MFs. The height method being used in this study, is the simplified state of COA. In this method, the COA method is simplified to consider only the height of each contributing MF at the mid-point of the base. The mean of maxima (MOM) method is the further simplified model of the height method. In this method the arithmetic mean of all values with maximum membership is considered. The fourth method, first of maxima (FOM) uses the union of the fuzzy sets and takes the smallest value of the domain with maximal membership degree. The last of maxima (LOM) is another method of defuzzification which uses the union of the fuzzy sets and takes the largest value of the domain with maximal membership degree. The middle of maxima (MOM) method is similar to the FOM and LOM. Instead of determining the defuzzified value to be the first or the last from all values, this method takes average of these two methods.

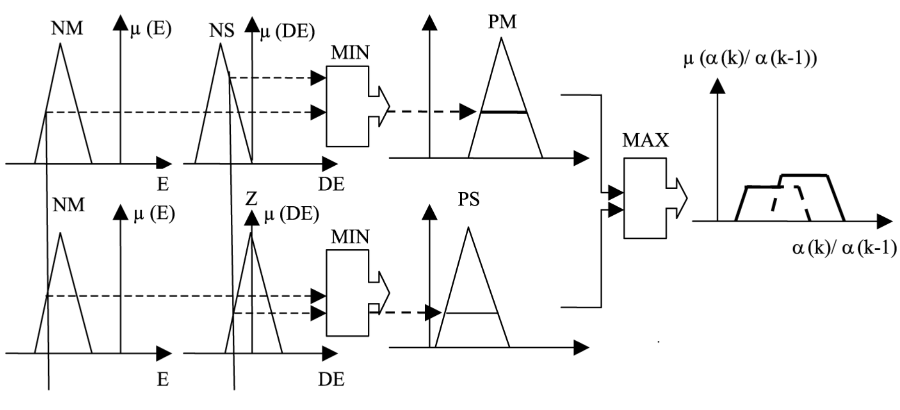


Figure 8.
Fuzzy-rule-based composition method by MAX-MIN principle

More quantitative description of the above-mentioned defuzzification techniques are given in Hellendoorn and Thomas (1993).

The best defuzzification method which can be used in each application is problem-dependent (Ross, 1995; Rao and Saraf, 1996). However, there are some criteria which can be used in the selection of a suitable defuzzification method (Hellendoorn and Thomas, 1993). The height method is both simple and very quick when compared with the centroid (COA) and the steady-state error of this method is small when compared with MOM, LOM, FOM methods.

In this study, the fuzzification is realized by using MFs of input variables, error (E) and derivative error (DE) for the output voltage of the converter. The variables used for fuzzification are E(K) and DE(K).

During control the following steps are performed:

(1) First, measured tube voltage is compared with the desired value to obtain the error signal (E). The error and the derivative error (DE) are converted into per unit by dividing into the desired voltage value (V_{ref}). Using the per unit error the degree(s) of the MF is (are) obtained.

(2) Derivative error (DE) is obtained by comparing the errors of the last two control steps and used in calculation of the degree(s) of the derivative error MF.

(3) The degree(s) of output MF is (are) calculated using the SUP-MIN method.

(4) Defuzzification is achieved using the height method.

The rules which should be activated for a specific input signal condition is determined by fuzzy controller using the fuzzy rule base and then the effective control action is obtained using the composition operation of MAX-MIN method.

It is evident that for any input data E (error) and DE (derivative error), only four rules will be valid in the entire rule base given in Table I.

6. Simulation of the system

For verifying the control strategies discussed above, the combination of mathematical model and fuzzy controller is simulated for the following operating conditions. The dc link capacitor has an initial arbitrary voltage of 140 V and the converter is connected to ac mains (220 V). The ac line inductance is 4.5 mH and the load is considered as a resistor with resistance value equal to ratio of the tube voltage to its current (125,000/0.1) referred to the primary side. The sampling time used in feedback control is 33.33 μs.

Figure 9(a) shows the uncontrolled referred tube voltage for the conditions where the initial voltage of the dc link capacitor is 140 V. It is shown that the tube voltage has a ripple with peak to peak value of 20 V and frequency of 100 Hz, respectively.

Figure 9(b) shows the tube voltage referred to the primary side, dc link voltage and the phase-shift angle of the inverter for the case as in Figure 9(a). It is shown that the phase-shift angle changes according to fuzzy control method in such a way to keep the tube voltage constant at the set value, 160 V. This is the dc-link voltage value at the primary of the transformer corresponding to the rated output voltage value, 125,000 V.

7. Experimental results

The block diagram of the hardware used in this study is shown in Figure 10. In this figure, L_t, C_t and r_t are the leakage inductance, secondary layer capacitance and transformer

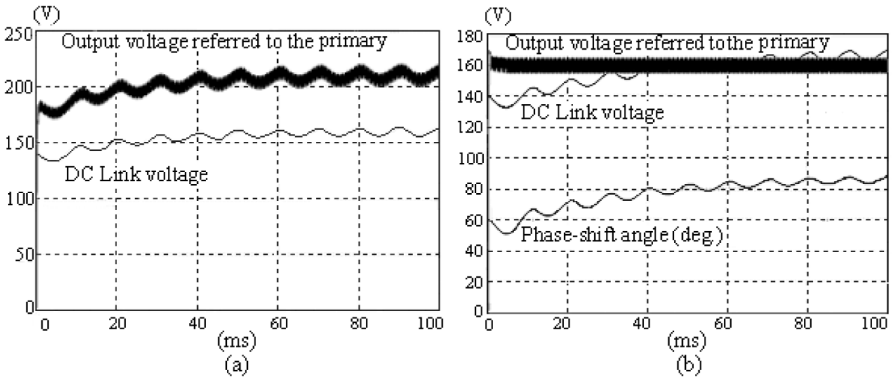


Figure 9.

Notes: (a) Referred tube voltage with no control $v_{C0}(t = 0) = 140$ V; (b) Referred tube voltage, dc link voltage and phase-shift angle with fuzzy control. $v_{C0}(0) = 140$ V

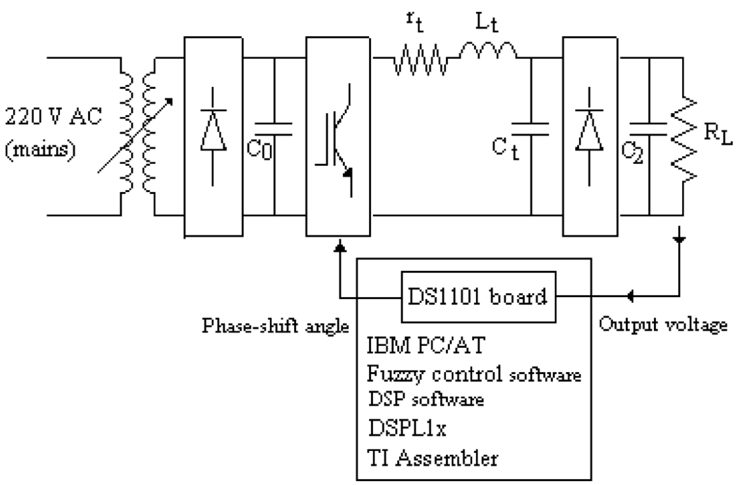


Figure 10.
The blocks diagram of the converter, equivalent circuits of the transformer and X-ray tube

winding resistance referred to the primary, respectively. The signals generated by microcontroller are sent to the inverter switches through an interface circuit.

The switches are intelligent power module dual type (IPM) manufactured by Mitsubishi Electric (PM200DSA060).

The dc link voltage is measured and converted into digital signals using DS1101 board. The measured tube voltage is compared with the reference level value to find a new phase-shift angle according to the fuzzy control method.

Using the above-mentioned control algorithm, the tube and output voltages of the inverter were recorded for the converter operating with the load as the referred X-ray tube equivalent resistance and the desired tube voltage of 15 V.

All the signals and parameters represented as the variable in the DSP's data memory can be recorded and graphically displayed using the DS1101 digital signal processor board, which contains a TMS320C14. TRACE14 software module is capable of saving the traced time histories on a readable ASCII file format. The real time traces of the tube voltage, the phase-shift angle and dc link voltage were saved on a disk and the results are shown in Figure 11. It is shown that while the dc link voltage varies the phase-shift angle changes in order to keep the output voltage constant at the desired value. For a sampling period of 320 μs, there are about 32 sampling periods in a time interval of 10 ms (ripple period of the dc link voltage) during which the phase-shift angle is constant.

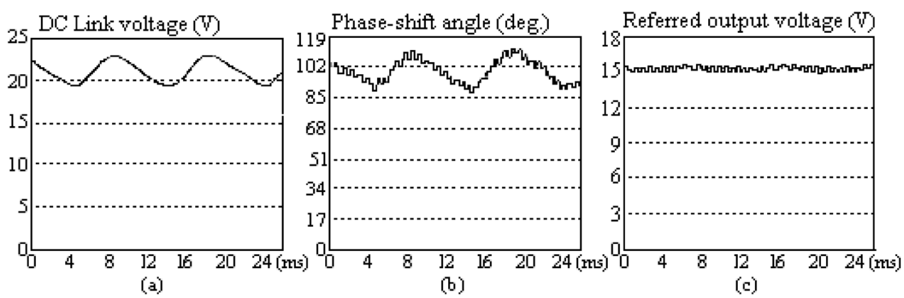
The rise- and fall-time of the tube voltage depend on the tube voltage smoothing capacitance. For the smoothing capacitance of 200 μF used in the experiments, they are determined as 750 μs and 1.4 ms.

8. Conclusions

In this study, we have presented fuzzy control approach to adjust the output voltage of the dc-dc converter using phase-shift PWM technique. The results obtained from the software and the hardware implemented in the laboratory indicate that the fuzzy control performs well in terms of voltage regulation, rise- and fall-time of the output waveform.

The inverter used in both mathematical simulation and experiments is a single-phase bridge operating around the resonant frequency of the system (lagging mode) so that switching losses of the transistors are decreased. The non-linearities of the transformer used in parallel resonant converter are incorporated in basic converter operation, rather than as parasitic elements that interfere with basic operation of the converter.

Simulation and experimental results illustrated that the control system is capable of eliminating the 100 Hz ripple in the output voltage and maintaining a voltage level set by the user only with a ripple at inverter frequency. The amplitude of the ripple at inverter frequency can be decreased by using a filter at the output of the output rectifier. The rise time which is an important criterion for the quality of the output voltage can be minimized by initially charging the dc-link capacitor to a desired level before the system starts operating. The findings here suggest that fuzzy control is a good choice for controlling a dc-dc converter to obtain a high quality output voltage waveform. The chief advantage of designing and implementing the proposed controller is that controller design does not require explicit knowledge of the converter dynamics, which is a useful feature when dealing with converter parameter uncertainties.



Notes: (a) dc-link voltage (b) phase-shift angle (deg.) (c) converter output voltage

Figure 11. The real time traces

References

Bhat, A.K.S. and Swamy, M.M. (1989), "Analysis and design of a high-frequency parallel resonant converter operating above resonance", *IEEE Trans. Aerospace Electron. Syst.*, Vol. 25, pp. 449-58.

Bhat, A.K.S. and Swamy, M.M. (1990), "Analysis and design of a parallel resonant converter including the effect of a high-frequency transformer", *IEEE Trans. Ind. Electro.*, Vol. 37 No. 4, pp. 297-306.

Bose, B.K. (2002), *Modern Power Electronics and AC Drives*, Prentice-Hall, Upper Saddle River, NJ.

Chin-Teng, L. and Lee, C.S.G. (1996), *Neural Fuzzy Systems: A Neuro-Fuzzy Synergism to Intelligent Systems*, Prentice-Hall, Upper Saddle River, NJ.

Eskandarzadeh, I. (1996), *Design and Control of a Phase-Shift PWM Resonant Converter for X-ray Generator*, Electrical and Electronics Engineering Department, The Middle East Technical University, Ankara.

Grossner, N.R. (1967), *Transformer for Electronic Circuit*, McGraw-Hill, New York, NY.

Hellendoorn, H. and Thomas, C. (1993), "Defuzzification in fuzzy controllers", *Intelligent and Fuzzy System*, Vol. 1, pp. 109-23.

Hino, H. (1989), "High-frequency parallel resonant converter for X-ray generator utility parasitic constants of high voltage transformer and cable", *Proceedings of Eleventh International Telecommunications Energy Conference (INTELEC 89), Italy, October 15-18*.

Lasdon, L.S. and Waren, A.D. (1989), *GRG2 User's Guide*, Department of Management Science and Information System, University of Texas, Austin, TX.

Mclyman, C.W.T. (1978), *Transformer and Inductor Design Handbook*, Marcel Dekker Inc., New York, NY.

Mattaveli, P., Rossetto, L. and Spiazzi, G. (1997), "General-purpose fuzzy controller for dc-dc converters", *IEEE Trans. Power Electronics*, Vol. 12 No. 1, pp. 79-86.

Patyra, M.J. (1996), "Design consideration of digital fuzzy logic controller", in Patyra, M.J. and Mlynek, D.M. (Eds), *Fuzzy Logic: Implementation and Applications*, Wiley, Chichester.

Rao, D.H. and Saraf, S.S. (1996), "Study of fuzzification methods of fuzzy logic controller for speed control of a DC motor", *Proceedings of the 1996 International Conference on Power Electronics, Drives and Energy Systems*, Vol. 2, pp. 782-7.

Ross, T.J. (1995), *Fuzzy Logic with Engineering Applications*, McGraw-Hill, New York, NY.

Sun, J.M., Lakunath, K.G.D. and Nakaoka, M. (1996), "Feasible characteristic evaluations resonant PWM inverter-link dc-dc high-power converters using high-voltage transformers parasitic components", *Proceedings of International Conference and Exhibition on Power Electronics, Drives and Motion (PCTM)*, pp. 629-38.

Vandelac, J.P. and Ziogas, P.D. (1988), "A dc to dc PWM series resonant converter operated at resonant frequency", *IEEE Trans. Industrial Electronics*, Vol. 35 No. 3.

Corresponding author
İres İskender can be contacted at: iresis@gazi.edu.tr