A Novel Soft Switching Based Fuzzy Logic Control For Single Phase Inverter

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Abstract. This The Pulse Width Modulation (PWM) DC-to-AC inverter has been widely used in many applications due to its circuit simplicity and rugged control scheme. It is however driven by a hard-switching pulse width modulation (PWM) inverter, which has low switching frequency, high switching loss, high electro-magnetic interference (EMI), high acoustic noise and low efficiency, etc. To solve these problems of the hard-switching inverter, many soft-switching inverters have been designed in the past. Unfortunately, high device voltage stress, large dc link voltage ripples, complex control scheme and so on are noticed in the existing soft-switching inverters. This proposed work overcomes the above problems with simple circuit topology and all switches work in zero-voltage switching condition. Comparative analysis between conventional open loop, PI and fuzzy logic based soft switching inverter is also presented and discussed.

Introduction

The widespread demand of improved power control and conversion has accelerated the need for advanced converter topologies. DC to AC converters (inverters) with improved efficiency and EMI performance, minimized thermal control needs, increased frequency and decreased size are being sought for many applications. This necessitates inverter circuits designed to reduce switching stress and losses in the power semiconductor switching devices. “Soft” switching provides an effective means of reducing device stress and switching losses [1-4]. The term soft switching means the devices are switched only when the voltage across the device and/or current through the device is zero resulting in zero voltage switching (ZVS) or zero current switching (ZCS). In recent years ZVS in medium to high power voltage source inverters has attracted increased attention. The most common soft switching circuits use a LC resonant tank to link the power supply to the switching circuit [3]. Normally the resonant circuit oscillates between zero and twice the supply voltage and ZVS occurs when the link voltage is zero. More versatile circuits do not rely on the natural resonant cycle, but use auxiliary switches to trigger ZVS or ZCS.An improved state of the art soft switching technique was proposed in. However, the controls of the auxiliary switches in all the above mentioned circuits [4-8] have been obtained by means of analog and digital circuitry. The control sequence being strictly dependent on the value of the resonant circuit components and the inverter load current, precise sensing of voltage and current parameters of the link circuit is required. Without the precise knowledge of control inputs (currents and voltages) the performance of the ZVS scheme proposed in gets degraded.

In recent years, fuzzy control has been investigated for many industrial applications. Recently fuzzy logic control has been successfully applied to a small but growing number of PWM inverters used for a variety of applications. Fuzzy controllers are very effective in handling ill defined or vague systems, and systems that are not easily defined mathematically. They are also robust and can effectively control a system even though the input signals to the fuzzy controller may
be noisy. The main use of fuzzy control systems is based on empirical rules and is more effective. Fuzzy systems are easily upgraded by adding new rules or new features to improve performance. Fuzzy control can be used to improve existing traditional control systems by adding a layer of intelligence to the current control method.

**Conventional Method**

**Open loop method**

The h-bridge formed by the switches $s_1$, $s_2$, $s_3$, $s_4$ performs forward power transfer where $s_1$-$s_2$ transfers the power during the positive half-cycle of output and $s_3$-$s_4$ transfers the power during the negative half-cycle of output. At which switches $s_1$,$s_3$ operates at high frequency (i.e., 50 kHz) and switches $s_2$,$s_4$ operates at low frequency (i.e., 50 Hz). The detailed block diagram of the proposed inverter is shown in figure 1.

**Operation and principal of inverter**

**Equivalent circuit model**

Equivalent circuit model is as shown in Fig. 2. The switch $S_i$ corresponds to $S1$ during forward power transfer for positive half-cycle and it corresponds to $S3$ during negative half-cycle. Since unipolar control is preferred control, switch $S2$ is always “ON” during the low-frequency (e.g., 60/50 Hz) positive cycle and switch $S4$ is always “ON” during the low-frequency negative half cycle.

To illustrate the soft switching characteristics of the proposed technique, the operation can be divided in to seven operating intervals. The operating waveforms in different intervals of operation are shown in figure 3. At the start of the switching period, it is assumed that the equivalent switch $S_i$ is off and the switch $S_{dc}$ is on. The load current is freewheeling through the diode $D_a$. Let the voltage across the resonant capacitor $C_r$ be $V_a$. The resonant capacitor is assumed large enough so that the voltage across it is assumed approximately constant, however changes slightly. The inductor current $i_{Lr}(i_{Lr}(0-) = -I_a)$ is flowing through the resonant capacitor $C_r$ and switch $S_{dc}$. Initially the switch $S_{dc}$ is in ON state. Whenever the supply is given to the circuit the voltage across $V_{link}$ and $V_{dc}$ starts increasing. Then a breach occurs, at a particular instant the voltage starts dropping and reaches zero, at that period the switches $S_{dc}$ and $S_1$ starts conducting simultaneously. Whenever the voltage across $V_{link}$ comes to zero the switch $S_{dc}$ will starts conduct and whenever the voltage across $V_{dc}$ comes to zero the switch $S_1$ will starts conducts which has been stated below in the waveforms. Related inductor and capacitor current and voltages has also been shown in figure 4 and the equivalent circuit with different operating intervals are given in figure 3 (a)-(g). The snubber capacitor, $C_s$ starts resonating with the resonant inductor $L_r$ which has been shown in the figure a. When the dc bus voltage ($V_{Link}$) reaches zero at $t_1$ the diode $D_a$ starts conducting. The current through $L_r$ ($i_{Lr}$) linearly ramps up and reaches $-I_0$ at $t_2$. The switch $S_d$ and $S_1$ are both gated within this interval. The equivalent circuit has been shown in the figure b1. The switch $S_i$ turns on with ZVS. The inductor current rises linearly until it reaches the output current $I_o$. 
The diode (Da) current ramps down and reach zero. Then the reverse recovery current of the diode Dₐ starts flowing. At the end of this interval the diode stops conducting and enters the blocking mode [4] is shown in figure.b. The current through Lₚ continues to increase due to resonance between Lₚ and Cₛ. The capacitor Cₛ is charged until the resonance brings its voltage Vₚₙ to Vdc and the voltage Vₘ reaches zero is shown in figure.c. The blocking voltage of the diode Dₐ increases and reaches Vdc [5]. The circuit diagram depicting this interval of operation is shown in figure.d. The dc link switch voltage Vₘ tries to go negative but is clamped by the anti-parallel body diode Dₐdc of the switch, which starts conducting. The switch Sₜₐ should be gated within this interval at time tₕ (tₚₕ < tₕ < tₗₖ) to obtain zero-voltage turn-on. The resonant inductor current iₔₚₚₖ reaches the output load current value (Iₒ) at tₖ [11]. The circuit diagram depicting this interval is shown in figure.e. The dc link switch turns on with zero voltage which is shown in figure.f. The resonant inductor current iₔₚₖₜ₟ₚₜₜ arms down and reaches zero at tₗ and goes negative, while the dc link switch current increases.

**PI Closed Loop**

PI controller have two components: the first component, proportional control which generates an output signal proportional to error and second component is integral control, takes into account the error history, and generates output proportional to the integral of error. Proportional controller (Kp) will have the effect of reducing the rise time but, never eliminate the steady-state error [10]. An integral control (Ki) will have the effect of eliminating the steady-state error, but it
may make the transient response worse [1]. Effects of each controller parameters kp, and Ki on a closed-loop system are summarized in Table.2 shown below. The PI values are obtained by tuning general inverter transfer function by using MATLAB tuner block. The results obtained in closed loop using PI controller is more desirable than that of the results obtained in open loop condition.

**Table 1. Inverter Rating**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>Input voltage</td>
<td>220 V</td>
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<td>Input current</td>
<td>2.5 A</td>
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<tr>
<td>Input power</td>
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<td>Output voltage</td>
<td>231 V</td>
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<tr>
<td>Output current</td>
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<td>Output power</td>
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<td>Total loss</td>
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<tr>
<td>Voltage stress</td>
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**Table 2. Tuned PI values**

<table>
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<td>Kp</td>
<td>1.2</td>
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<tr>
<td>Ki</td>
<td>0.08</td>
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</table>

**Fig.5. PI Controller based Inverter**

**Fig.6. Fuzzy logic Controller based Inverter**

**Proposed Method**

**Fuzzy logic controller**

In this paper a fuzzy logic controller is proposed and investigated for the control of the auxiliary switches of the DC link voltage and inverter switch circuit described in. The voltage across the load output voltage are fuzzified, and used as the input fuzzy signals to the rule-based fuzzy controller.

The output of the fuzzy controller is used to control the state of the auxiliary switches and inverter four switches i.e. on or off. The input and output signals are defined by a set of linguistic variables which are characterized by their associated membership functions. A fuzzy rule base is developed that relate these input signals to the fuzzy controller output. The fuzzy outputs (in linguistic terms) are then defuzzified to obtain a crisp output signal. This crisp output signal is then used to control the switching of the auxiliary switches of the dc voltage notching circuit. The fuzzy logic controller is capable of providing more robust control as compared to the existing methods.

**Design of Fuzzy logic controller**

Fuzzy logic controller is a rule-based controller. It consists of an input, processing and output stages. The input or fuzzification stage maps sensor or other inputs such as switches, thumbwheels and so on, to the appropriate membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output or defuzzification stage converts the combined result back into specific control output. The membership function is triangular, although trapezoidal and bell curves are also used, but the shape is generally less important than the number of curves and their placement. From three to seven curves are generally appropriate to cover the required range of an input value or the “universe of discourse” in fuzzy language. There are several different ways to define the result of a rule, but one of the most common and simplest is the “max – min” inference method, in which the output membership function is given by the truth value generated by the promise.
Fuzzy rule has a 7 x 7 decision table with two input variables and one output variable. The look up table for the input and output rules defined for seven linguistic variables (NB, NM, NS, ZE, PS, PM, PB) that stand for negative big, negative medium, negative small, zero, controller converges to the reference value, positive small, positive medium and positive big respectively are given in Table.3.

### Table 3 Fuzzy rule base

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### Simulation for Proposed Inverter

Fuzzy logic is a mathematical logic that attempts to solve problems by assigning values to an imprecise spectrum of data in order to arrive at the most accurate conclusion possible. It is designed to solve problems in the same way that humans do by considering all available information and making the best possible decision given the input. In this section, an explanation of the design and analysis of the fuzzy logic controller is presented. The main simulation circuit of the proposed inverter using fuzzy logic controller is shown in figure.8. The output voltage can be varied from 120v to 140v for the required application and hence the output voltage obtained for closed loop system using fuzzy logic controller is 120v. Fig.8 Simulated waveforms for gate pulses $S_{dc}, S_1, S_2, S_3,$ and $S_4$, Resonant inductor current($L_r$), snubber capacitor voltage($C_s$), output voltage($V_o$) and output current($I_o$)

The simulation output result is as shown in figure 11. The red arrow indicate that period the capacitor voltage zero at this time switch will be ON. In this period switch achieve zero voltage switching.

### Salient Features of Proposed Inverter

Salient features of proposed inverter are as given below.

1) All the switches turn-on with zero voltage and the turnoff losses are reduced by lossless capacitive snubbers.
2) During reverse recovery, the di/dt is controlled by the resonant inductor.
3) Voltage stress on all the devices is limited to the dc bus voltage.
4) Fuzzy logic overcomes the mathematical difficulties of modelling highly non-linear systems.
5) Fuzzy logic responds in a more stable fashion to imprecise readings of feedback control parameters, such as the dc link current and voltage.
6) Fuzzy logic control mathematics and software are simple to develop and flexible for each modification.

Comparison of Conventional and Proposed Method

The proposed inverter is simulated in matlab environment using simulink. An open-loop controller, also called a non-feedback controller, is a type of controller that computes its input into a system using only the current state and its model of the system. A characteristic of the open-loop controller is that it does not use feedback to determine if its output has achieved the desired goal of the input. This means that the system does not observe the output of the processes that it is controlling. Consequently, a true open-loop system can not engage in machine learning and also cannot correct any errors that it could make. It also may not compensate for disturbances in the system. A dc-to-ac bridge inverter with 220v dc input was designed as per design procedure illustrated. the output frequency, is $f_o=50$ Hz and switching frequency, $f_s=50$ kHz. The top switches ($s_1$, $s_3$), in the full bridge inverter operate at high frequency, while the bottom switches ($s_4$, $s_2$) operate at low output frequency. $L_r$ is selected to be 32 mh to limit the di/dt of the anti-parallel diodes and recovery losses is negligible. Resonant frequency is chosen as $f_r=50$ kHz and resonant capacitor as $C_r=5$ µh. the output voltage can be varied from 120v to 140v for the required application and hence the output voltage obtained for open loop system is 138v.

The overall summary of the output is stated below in Table.4. It is clear that the performance obtained in the closed loop system is far better than the open loop system. The voltage stress has been reduced in closed loop system than that of the open loop system. The overall losses are mainly because of the switches and are considered to be as switching loss.

The results obtained in proposed method using Fuzzy logic system controller is more desirable than that of the results obtained in conventional condition. It is clear that the performance obtained in the proposed system is far better than the conventional system. The voltage stress has been reduced in fuzzy logic system than that of the open loop and PI control system. The overall losses are mainly because of the switches and are considered to be as switching loss.

Comparison of conventional and proposed method rating is as show in above table. For openloop method the voltage stress is 5V. In the closed loop method using PI controller the voltage stress is 4.4V and closed loop system using fuzzy logic controller the voltage stress is 4.2V. The red arrow indicate the reduced voltage stress in the fuzzy logic controller, so the fuzzy logic controller method the voltage stress is very low compare with the open loop and PI controller method.
Conclusion

The voltage stress behavior of the DC link soft switching inverter with conventional open loop, PI and fuzzy logic system controllers are presented and compared for voltage stress and switching loss. It is observed that the FLS controller gives much better voltage stress reduction. From the results of proposed inverter topology, it is observed that all the switches work under soft switching condition and freewheeling diodes are turned off under zero current condition which greatly reduces the reverse recovery problem of the diodes. Further, voltage stress on all the switches is very low and it is not greater than the dc supply voltage. The switching acoustic noise is very much reduced as the switching frequency is as high as 50 kHz and moreover $dv/dt$ and $di/dt$ are reduced significantly and as a result EMI is reduced. Furthermore, in the proposed method, very simple auxiliary switches control scheme is needed and the normal operation of the inverter is essentially the same as that of the hard switching inverter. It is validated by simulation results that FLS controller performs better.

References
