Soft Switching Three Phase Inverter with Two Auxiliary Switches

Mohammad Mahdavi†, Mohammad Reza Amini*, Amin Emrani*, and Hosein Farzanehfard**

†† Dept. of Electrical Engineering, Islamic Azad University, Khorasgan Branch, Isfahan, Iran
** Dept. of Electrical & Computer Engineering, Isfahan University of Technology, Isfahan, Iran

Abstract

In this paper, a new three phase soft switching inverter is presented. All of the semiconductor elements of this converter are soft switched. Employing only two auxiliary switches as DC-link switches and a simple control circuit are the advantages of the proposed inverter. The analytical equations and operating modes of the presented inverter are explained in details. The design considerations are presented and the experimental results verify the theoretical analysis.

Key Words: Quasi-resonant, Soft switching, Three phase inverter, Zero voltage switching (ZVS)

I. INTRODUCTION

Inverters have many applications in power electronics, such as AC motor drives, active power filters, and uninterruptible power supplies. To increase the efficiency of converters and to decrease electromagnetic interference, it is necessary to use soft switching techniques [1]–[3]. Among these techniques, quasi-resonant dc-link inverters have the advantages of zero voltage switching (ZVS) for the main switches, a low number of the auxiliary switches and low voltage stress on the main switches.

One of the main objectives of quasi-resonant dc-link inverters is achieving soft switching conditions with a minimum number of auxiliary circuit elements. The auxiliary circuit in [4] has three auxiliary switches and the auxiliary circuits in [5]–[9] have two auxiliary switches. Reducing the number of auxiliary switches simplifies the control circuit and decreases the inverter cost. Therefore, it is worth offering to provide soft switching inverters with one auxiliary switch [10], [11]. In [10], the number of auxiliary switches is reduced at the cost of employing extra elements including three diodes, coupled inductors and a resonant capacitor. The auxiliary circuit presented in [11] reduced the number of extra elements at the expense of adding a capacitive voltage divider at the inverter input and losing control over the zero voltage interval of the inverter DC-link. The control of the DC-link zero voltage interval, is used in some switching methods such as space vector modulation. The soft switching inverters presented in [12] and [13] have no auxiliary switch and the soft switching condition is achieved by a DC-link switch. The drawback of these inverters is that their DC-link switch is turned off under an almost zero voltage condition due to the existence of a leakage inductor in series with the DC-link switch, which causes a voltage spike across the switch at the turn off instant. To reduce this voltage spike, a passive turn off snubber must be used, which add extra losses to the circuit. Soft switching inverters usually do not have a passive snubber. The soft switching inverter presented in [14], in addition to having an auxiliary switch, requires such a snubber for the auxiliary switch.

A new soft switching inverter with two DC-link switches is proposed in this paper. These switches are turned on under the zero voltage zero current switching (ZVZCS) condition and off under the ZVS condition. Since the sources of the DC-link switches are connected together, and they are complimentary switched, their gate drive circuits become simple. The proposed inverter has a lower number of extra elements in comparison with previous converters while all of the switches are fully soft switched. Furthermore, the DC-link switches share the inverter current which considerably reduces the switches current stress.

The proposed inverter is introduced and its operating modes are discussed in section II. The design considerations of the proposed inverter are provided in section III and the experimental results of a 250W, 20kHz prototype inverter are presented in section IV. The presented experimental results confirm the theoretical analysis.

II. PROPOSED INVERTER DESCRIPTION AND OPERATION

The circuit configuration of the proposed soft switching inverter is illustrated in Fig. 1. The main inverter is composed of the switches S1 to S6. The auxiliary circuit consists of
the DC-link switches S_{a1} and S_{a2}, the coupled inductors L_{r1} and L_{r2}, and the capacitors C_r, C_1 and C_2. Due to circuit symmetry, L_{r1} is designed to be equal to L_{r2}, and C_1 is designed to be equal to C_2. To simplify the inverter analysis, the main inverter switches and the load are replaced with S_{inv} and I_o as shown in Fig. 2. Also diode D_o stands for the anti-parallel diodes of the inverter switches. In order to simplify the inverter operating analysis, all of the circuit elements are assumed to be ideal.

The main theoretical waveforms of the proposed inverter are presented in Fig. 3. The proposed inverter has six distinct operating modes in a switching cycle, as shown in Fig. 4. Before the first operating mode, it is supposed that S_{a1} is on and that S_{a2} is off. Also, it is assumed that switch S_{inv} is on, I_o is flowing through D_o and the L_{r1} current is increasing.

**Mode 1** ($t_0 \leq t < t_1$): When the L_{r1} current reaches I_o, D_o turns off under the ZCS condition and then the additional current flows through S_{inv}. The L_{r1} current is:

$$I_{L1}(t) = \frac{V_s}{L_{r1}}(t-t_0).$$  \hfill (1)

The L_{r1} current increases linearly until it reaches I_1 which is defined as the minimum required current of L_{r1} that guarantees the charging of C_r in mode 4. The design procedure of I_1 is illustrated in section III. The duration of this mode is:

$$\Delta t_1 = t_1 - t_0 = \frac{L_{r1}I_1}{V_s}. \hfill (2)$$

**Mode 2** ($t_1 \leq t < t_2$): At t_1, the states of the inverter main switches are changed. Due to C_r, the inverter main switches are turned off under the ZVS condition. This means that S_{inv} is turned off. Thus a resonance starts between C_r, C_{a2} and L_{r1} which increases the DC-link voltage. C_2 is designed to absorb the energy stored in the leakage inductance L_{r2} at the S_{a2} turn off instant. Therefore the discharging time of C_2 is negligible. The C_r voltage and the L_{r1} current equations are:

$$V_{C_r}(t) = Z_r(I_1-I_o)\sin(\omega_r(t-t_1)) + V_s(1-\cos(\omega_r(t-t_1)))$$ \hfill (3)

$$I_{L1}(t) = (I_1-I_o)\cos(\omega_r(t-t_1)) + \frac{V_s}{Z_r}\sin(\omega_r(t-t_1)) + I_o$$ \hfill (4)

where

$$\omega_r = \frac{1}{\sqrt{L_{r1}C_r}}, \quad Z_r = \frac{L_{r1}}{C_r}. \hfill (5)$$

This mode continues until the C_r voltage reaches V_s. Duration of this mode is:

$$\Delta t_2 = t_2 - t_1 = \frac{1}{\omega_r}\tan^{-1}\left(\frac{V_s}{Z_r(I_1-I_o)}\right). \hfill (6)$$

**Mode 3** ($t_2 \leq t < t_3$): At t_2, the C_r voltage reaches V_s and the diode D_2 turns on under the ZVS condition. Thus, a fraction of the L_{r1} linkage flux moves to L_{r2} and the current of L_{r2} begins to freewheel through the switch S_{a1} and the inductor L_{r2}. At the beginning of this interval, the L_{r1} current is:

$$I_{L1}(t_2) = I_1 = \sqrt{(\frac{V_s}{Z_r})^2 + (I_1-I_o)^2 + I_o}. \hfill (7)$$

The ampere-turns of the coupled inductors must be constant, so I_{L1} and I_{L2} are obtained as follows:

$$I_{L1} = \frac{I_1 + I_o}{2} \hfill (8)$$

$$I_{L2} = \frac{I_1 - I_o}{2}. \hfill (9)$$

In this mode the power flows from the source to the load. This mode continues until a change is required in the inverter switches.

**Mode 4** ($t_3 \leq t < t_4$): If the states of the inverter main switches need to be changed, S_{a1} must be turned off. Thus the ampere-turns of L_{r1} move to L_{r2} and the L_{r2} current increases. Therefore C_r begins to discharge. Note that a part of the L_{r2} energy used to charge C_1 is negligible since C_1 is a smaller capacitance in comparison with C_r. In this mode L_{r1} resonates with C_r and the C_r voltage decreases to zero. S_{a1} is turned off under the ZVS condition at the beginning of this mode. Also, S_{a2} can be turned on under the ZVZCS condition due to the conduction of D_2. The L_{r2} current and the C_r voltage in this mode are:

$$V_{C_r}(t) = V_s - Z_rI_1\sin(\omega_r(t-t_3)) \hfill (10)$$

$$I_{L2}(t) = I_1 \cos(\omega_r(t-t_3)). \hfill (11)$$

When the C_r voltage reaches zero, this interval ends. Thus, the duration of this mode is:

$$\Delta t_4 = t_4 - t_3 = \frac{1}{\omega_r}\sin^{-1}\left(\frac{V_s}{Z_rI_1}\right). \hfill (12)$$

**Mode 5** ($t_4 \leq t < t_5$): In this interval, the diode D_o turns on under the ZVS condition and the L_{r2} current is discharged to the input source via D_o. Thus, the switch S_{inv} can be turned
on under the ZVZCS condition. The $L_{r2}$ current decreases linearly from $I_2$ to zero. Thus the $L_{r2}$ current is:

$$I_{Lr2}(t) = I_2 - \frac{V_s}{L_{r2}}(t - t_4)$$

where

$$I_2 = I_{Lr2}(t_4) = \sqrt{I_1^2 - \left(\frac{V_s}{Z_r}\right)^2}.$$  \hspace{1cm} (14)

Duration of this mode is:

$$\Delta t_5 = t_5 - t_4 = \frac{L_{r2}I_2}{V_s}.$$  \hspace{1cm} (15)

Mode 6 ($t_5 \leq t \leq t_6$): At $t_5$, the $L_{r2}$ current reaches zero and the diode $D_2$ turns off under the ZCS condition. In this mode the $L_{r2}$ current reverses and flows through $S_{a2}$ and $S_{inv}$.

III. DESIGN CONSIDERATION OF THE PROPOSED SOFT SWITCHING INVERTER

Designing the proposed circuit involves the selection of $L_{r1}$, $C_{s1}$, $C_r$ and $I_i$. The inductor $L_{r1}$ provides the zero current switching condition for the DC-link switch at the turn on instant.

Therefore its value can be selected like that of a regular turn on snubber [15]. The capacitor $C_{s1}$ provides the zero voltage switching condition at the switch turn off instant for the DC-link switch. Therefore its value can be selected like that of a regular turn off snubber [15].

$C_r$ is designed to be much larger than $C_{s1}$ and therefore the resonance time between $C_{s1}$ and $L_{r1}$ in mode 4 is negligible.

A practical design for the ratio of $C_r/C_{s1}$ is between 10 and 20.

The initial current $I_i$ must be large enough to guarantee the discharging of $C_r$ in mode 4. Thus according to equation (10):

$$Z_rI_1 \geq V_s.$$  \hspace{1cm} (16)

By substituting $I_1$ from equation (7) in equation (16), the following relation is obtained:

$$I_i \geq I_o + \sqrt{I_o^2 - 2I_o \frac{V_s}{Z_r}}.$$  \hspace{1cm} (17)
It is necessary to design for the worst possible condition. The right side of relation (17) is at its maximum when \( I_o \) is maximized. In practice, to compensate for the effect of \( C_{s2} \) and \( C_{s1} \) in the second and fourth modes, \( I_i \) must be designed 20 percent larger than its calculated value. Thus the following equation is obtained:

\[
I_i = 1.2(I_{om} + \sqrt{I_{om}^2 - 2I_{om} \frac{V_s}{Z_r}})
\]  

(18)

where \( I_{om} \) is the maximum of \( I_o \).

**IV. EXPERIMENTAL RESULTS**

A prototype of the proposed soft switching inverter is implemented at a 20kHz switching frequency. The input voltage \( (V_s) \) is 100V and the output load power is 250W with a 0.9 power factor. The output frequency is 400Hz. According to the design procedure, the auxiliary circuit parameters are calculated as \( C_r = 10nF, C_s = 470pF, \) and \( L_r = 18\mu H \).

A photograph of the prototype inverter circuit is shown in figure 5. The switches in the inverter are IRFP460. A 470\( \mu F \) capacitor is placed at the rectifier output and the inverter input. The inverter input power is produced with a rectifying 50Hz voltage that was obtained from an autotransformer. The
inverter load is a simple R-L load. A photograph of the prototype control circuit is shown in Fig. 6. The gate pulses are produced with an ATMEGA16 microcontroller and the gate drivers are IR2113.

The experimental results are illustrated in figures 7, 8 and 9. The voltages and currents of the auxiliary switches are illustrated in Fig. 7. The inherent anti-parallel diodes of the auxiliary switches are considered as $D_1$ and $D_2$. Thus, sum of the switches and the anti-parallel diodes are shown in this figure. It can be seen that the auxiliary switches are turned on under the ZVZCS condition and turned off under ZVS condition. The voltage and current waveforms of the inverter main switches along with the DC-link voltage are shown in Fig. 8. It can be seen from this figure that the inverter main switches are turned on and off under the ZVS conditions. Fig. 9 shows the inverter three phase output currents.

In Fig. 10 the proposed inverter efficiency is compared with a hard switching inverter at several output power levels. It can be seen that the efficiency of the proposed inverter is improved by about 2 percent at nominal power. This improvement is one of the several advantages of soft switching. Other advantages include a reduction in electromagnetic interference and an increase in the switching frequency of the inverter.

V. CONCLUSION

In this paper, a new soft switching three phase inverter is presented. To achieve soft switching for the main switches, the converter uses two DC-link switches. The inverter main switches are turned on and off under the zero voltage condition...
as illustrated in the experimental results. The experimental results confirm the theoretical analysis of the proposed converter.

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REFERENCES


Mohammad Mahdavi was born in Isfahan, Iran, in 1984. He received his B.S. and M.S. in Electrical Engineering from the Isfahan University of Technology, Isfahan, Iran, in 2006 and 2009, respectively. He is currently pursuing his Ph.D. in Electrical Engineering at the Isfahan University of Technology. His research interests include soft switching techniques and PFC converters.

Mohammad Reza Amini was born in Isfahan, Iran, in 1984. He received his B.S. and M.S. in Electrical Engineering from the Isfahan University of Technology, Isfahan, Iran, in 2006 and 2009, respectively. He is currently pursuing his Ph.D. in Electrical Engineering at the Isfahan University of Technology. His research interests include soft switching techniques in DC-DC and DC-AC converters.

Amin Emrani was born in Isfahan, Iran in 1985. He received his B.S. and M.S. in Electrical Engineering from the Isfahan University of Technology (IUT), Isfahan, Iran, in 2007 and 2010, respectively. He has been teaching at the Islamic Azad University Khorasgan (branch) for three years. He has also been working in Switching Power Supply Lab in IUT for five years. He is currently pursuing his Ph.D. in Electrical Engineering at the State University of New York (Binghamton University). His research interests include solar cells, MPPT, high frequency soft switching converters, power factor correction, active power filters and high frequency electronic ballasts.

Hosein Farzanehfard was born in Isfahan, Iran in 1961. He received his B.S. and M.S. in Electrical Engineering from the University of Missouri, Columbia, Missouri, USA, in 1983 and 1985, respectively. He received his Ph.D. from Virginia Tech., Blacksburg, Virginia, USA, in 1992. Since 1993, he has been a faculty member in the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan. Iran. He is currently an Associate Professor and President of the Information and Communication Technology Institute. His research interests include high frequency soft switching converters, pulse power applications, power factor correction, active power filters and high frequency electronic ballasts. He is the author of more than 70 technical papers published in journals and conference proceedings.