ISSN 2228-9860 eISSN 1906-9642 CODEN: ITJEA8

International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

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A Soft Switching DC-Link Quasi Resonant Three-Phase Inverter for AC Servo-Motor Drive Applications

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Paper ID: 12A1N

Volume 12 Issue 1

Received 04 September 2020
Received in revised form 02 November 2020
Accepted 04 November 2020
Available online 09 November 2020

Keywords:
Soft-switching; Quasi-resonant DC link snubbers; Servo motor drive; Hard-switched inverter, Power loss; Circuit simulation.

Abstract

This paper presents a soft-switching circuit of a three-phase inverter for servomotor driver. The soft switching is achieved using an auxiliary quasi-resonant circuit on the DC link. The principal of operation and design steps are described in details. Soft-switching operation condition is validated in this circuit by means of simulations and experimental work. A prototype of 3-kW inverter is implemented and tested. The conductive noise is measured for the proposed AC servo motor drive and compared with that of conventional hard-switched inverter. The power loss analyses are carrier out to verify the effectiveness of the proposed inverter.

Disciplinary: Electrical Engineering and Technology.

Cite This Article:

Alghamdi, A. S., Sayed, K., Abokhalil, Awan, A. B., Mohamed A. Zohdy, M. A. (2021). A Soft Switching DC-Link Quasi Resonant Three-Phase Inverter for AC Servo-Motor Drive Applications. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies, 12*(1), 12A1N, 1-13. http://TUENGR.COM/V12/12A1N.pdf DOI: 10.14456/ITJEMAST.2021.14

1. Introduction

AC servo motors or Permanent Magnet Synchronous Motors (PMSM) has have numerous advantages over induction motor such as compact size, better efficiency, lighter weight, no slip, and fast acceleration [1-2]. As a result, these motors are usually utilized in speed or position controlled drives in high performance applications such as robots, CNC machines, and etc. Three-Phase Inverters operating at higher switching frequencies have several applications in power-electronic devices, like ac power sources, active-power filters, motor drives, distributed generation (DG) systems and uninterruptible power supplies (UPS). The major motive to augment switching frequency is to reduce passive components' size and weight and the composition of signals with higher-order harmonic [3]–[4]. Conversely, operation at higher-switching frequency increases the electromagnetic interference and switching loss. Several works have been focused on applying different methods to minimize the switching losses in voltage-fed inverters, using passive or active auxiliary resonant circuits. The frequency of switching has to be increased for maximizing the filtering components' sizes and reducing audio noises. However, higher switching frequency for inverters with hard switching, results in increasing switching losses. This eventually augments sizes of heat sinks and snubber circuits. Moreover, radio-frequency interference reproduces, and overall efficiency is reduced [5]. Hence, applying soft-switching techniques is essential to cope with these issues, [6]–[8]. The technology of soft-switching is exceedingly used on power electronic circuits for diminishing circuit losses and noise efficiently by controlling the semiconductor device under zero-voltage and/or zero current soft switching (ZVS/ZCS) commutation. For these reasons, soft-switching is the most promising candidate for the next development of inverter technology. One class of soft-switching inverters is the quasi-resonant (QR) dc-link inverters that can be regulated using pulse-width modulation (PWM) technique [9]–[14]. The configuration of these inverters is featured by using a series switch (dc-link switch) to separate the inverter dc-link from the input power supply while a resonant capacitor is positioned in parallel with the inverter dc-link. The QR inverter scheme generates zero-voltage instants in the DC-link at controllable periods that can be synchronized with typical PWM switching action, thus assuring a zero-voltage soft switching (ZVS) operation of inverter semiconductor devices. In different words, the dc-link power switch is opened when a change in the status of the inverter power switches is required and the discharge of the resonance-capacitor takes place through an additional circuit. Consequently, the inverter's semiconductor switches status can be altered under ZVS condition. To discharge or charge the capacitor of dc-link, usually, two or more switches are required for the auxiliary circuit. Since all QR dc-link (DCL) inverters need a power switch in the essential power flow path and they are appropriate for low and medium power applications.

Recently, the power conversion circuitry topologies are developed using the modern semiconductor devices like IGBTs and MOSFETs. However, rise in inverter switching frequency becomes indispensable in order to improve its controllability, to reduce undesired acoustic sound, and to downsize the equipment [15-16]. However, in conventional hard switching inverters, the power losses resulting from switching of power semiconductor devices as well as EMI noise levels become larger. In addition, in the power converter / inverter which is utilized for variable speed servo motor drives, the new problems are breaking out due to high dv/dt such as the high-frequency leakage current which circulates into the grounded parts through the stray capacitance between the stator windings and the frame of the motor, the induced voltage on motor shaft and the bearing current. On this account, the inverter AC servo drive installations with the high speed power semiconductor devices such as IGBTs, MOSFETs etc. tend to have these problems more and more obviously.

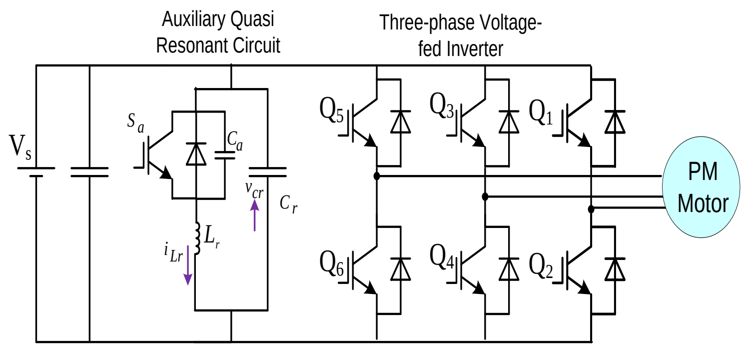

Figure 1: Proposed soft switching inverter for AC servo motor drive using QR dc link snubbers.

For tackling the aforementioned problems, the soft switching techniques are proposed for power conversion circuits. These techniques make the semiconductor devices work under the zero current or zero voltage mode transitions. Generally, based on auxiliary circuitry location, the three-phase voltage source soft-switching inverters are classified into dc-bus-side topologies [17]–[21] and load-side topologies [22]–[27]. The operation at optimal efficiency for a given performance is one of the challenges facing developers of servo-motor applications. For this reason, power loss calculation of power converters has been considered due to the impact of various PWM techniques used for vector-controlled servo drives [28]–[31] and direct torque controlled variable-speed drives [32]. However, this design depends strongly on thermal performance and power losses calculation. Both of these key factors decide the reliability and power density of power converters [33].

This paper deals with the three-phase soft switching inverter using the QR DC bus snubbers for the AC servo motor drives. Moreover, it presents the evaluations for the soft-switched QR snubber circuit. The conductive noise of the studied QR snubber assisted voltage-fed inverter is measured for AC servo motor drive and compared with that of the conventional hard switched three-phase inverter.

2. Circuit Topology

The control system of AC-servo-motor drive is described in Figure 1. This configuration is based on three phase voltage soft switching inverter assisted by utilizing QR DC-link snubbers. Figure 1 illustrates the main parts of a PWM servo motor drive. The input three-phase voltage is rectified and filtered to produce a DC-link voltage for inverter stage of drive. The stator winding inductance of the servo motor plays as a low-pass filter for the studied inverter. The inverter consists of three pairs of IGBT semiconductor switches with associated reverse conducting diodes. Each pair of IGBT switches enables the output voltage for each phase of the motor. However the inverter consists of three legs, each leg consists of one pair of IGBT semiconductor switches. All are driven with the aid of the control electronics to produce a higher frequency gate drive pulses. An auxiliary circuit is inserted between the DC-rectified input and the DC-bus of the three-phase inverter. The suggested auxiliary circuit is utilized to enable zero-voltage duration of the DC-link at the desirable switching instant. Thus the corresponding semiconductor devices in three-bridge legs can achieve ZVS condition.

The soft switching operation of inverter is based on the loss-less capacitors using LC quasi-resonance phenomenon. Employing this phenomenon, the DC bus line voltage of quasi-resonance capacitor C_r that is associated in parallel to auxiliary switch is brought down to the zero voltage. Consequently, the power switches of inverter bridge-arms can realize ZVS/ZCS turning-on and ZVS turning-off. This circuit topology is composed with the switch S_{c1} of the circuit which clamps the DC- link at the DC input voltage V_s, the auxiliary switches S_{a1} and S_{a2} for transferring resonant mode, the QR inductance L_r, the resonant capacitor C_a connected in parallel to the switch S_{a2} and the resonant capacitor C_r connected in parallel to inverter switch S_{inv} as depicted in Figure. 2.

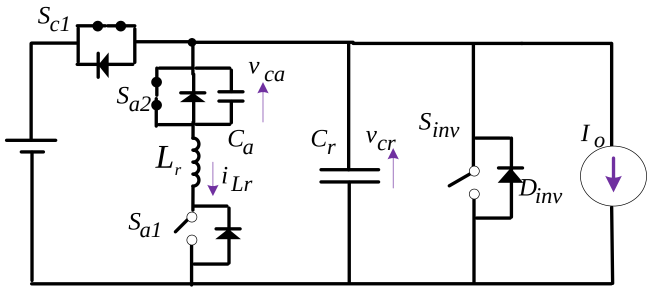

Figure 2: Auxiliary QR dc-link snubber equivalent circuit.

3. Theory of Operation

The studied ZVT power converter has special advantages including the operation of main IGBTs and diodes with ZVS and a reduced current and voltage stresses on the devices, namely the same as their PWM counterpart. Additional key advantages are simple circuit topology, the utilization of the same resonance tank for both upper and lower branches, and fully utilizing all diodes built-in power IGBTs, thus reducing the total component count and cost. These are very desirable features for high power high frequency converters, where power IGBTs are used. This makes the studied converter particularly beneficial for servo motor drives, which require multi-phase full-bridge ac inverters. The consequent theoretical analysis and efficiency calculations are supported by simulation. The ZVT-cell can also be modified to provide ZVS for all chopping and commutating switches of a servo motor drive.

This model is utilized in order to explain the operation modes of the QR DC-link circuit. Figure 2 shows the equivalent circuit of single-phase arm. The operation waveforms are shown in Figure 3. The related equivalent circuits of all modes are represented in Figure 4.

Mode 0 (- t_0): Both the auxiliary (S_{a2}) and the voltage clamps switch (S_{c1}) $_2$ are in operation. The current is flowing to the load.

Mode 1 (t_0-t_1): The switching gate pulse is applied to the inverter main power switches. Switch S_{a1} is turned on at the ZCS condition. Therefore, the current i_{Lr} of the QR inductor is boosted enough to pull down the voltage across the main QR capacitor to zero volt. This is considered as an energy storage interval (t_0-t_1) which is required for storing resonant energy in the resonant inductor L_r to assure that the voltage on resonant link does decrease down to zero, during the ramp down interval. The energy storage interval begins with turning-on the auxiliary switch S_{a1}. Then,

$$i_L(t) = \frac{V_{in}}{L_r}(t - t_0) \qquad (1).$$

This interval (energy storage interval) terminates when current in resonant inductor reaches the maximum value $i_L(t_1)$. Then,

$$i_L(t_1) = \frac{V_{in}}{Z_r} = i_L(t)_{\max} \qquad (2).$$

The period of the energy storing interval is

$$\Delta t_1 = \frac{\pi}{2\omega_r} \qquad (3).$$

Mode 2 (t_1-t_2): When the current in QR inductor i_{Lr} reaches to the initial QR current I_{boost1}, both S_{a2} and S_{c1} are turned off under ZVS condition, while quasi-resonance begins with L_r, C_r and C_a.

The resonant current in this mode is given by

$$i_{Lr} = I_o + \frac{V_S}{Z_0}(t - t_1) \qquad (4).$$

Interval 2 starts when the diode D stops conduction. The elements L_r and C_r represent a series resonance circuit. The corresponding differential equations are

$$i_{Lr}(t) = C_r\frac{dV_{cr}}{dt} + C_a\frac{dV_{ca}}{dt} \qquad (5),$$

$$L_r\frac{di_{Lr}(t)}{dt} = V_s - v_{cr}(t) \qquad (6),$$

with initial conditions $i_{Lr}(0) = I_m$ and $v_c(0) = -Vo$.

The solutions for the above equations are

$$i_{Lr}(t) = I_o + \frac{V_S + V_0}{Z_0}\sin(\omega_o t) \qquad (7),$$

$$v_{cr}(t) = V_s - (V_s + V_o)\cos(\omega_o t) \qquad (8),$$

$$v_{Lr}(t) = (V_s + V_o)\cos(\omega_o t) \qquad (9).$$

Mode 3 (t_2-t_3): When the voltage v_{cr} across the main capacitor is brought to zero, the reverse diode which is parallel to switch S_{inv} conducts and then S_{inv} turns on at ZVS/ZCS condition. The current in inductor is linearly decreasing. This mode ends when $I_{Lr}(t)$ reaches to zero.

$$i_{Lr}(t) = -\frac{V_S}{L_r}(t - t_2) + I_3 \quad (10).$$

Mode 4 (t_3-t_4): The current through QR inductor i_{Lr} starts increasing in the opposite direction and it raises voltage of capacitor to source DC voltage V_s. During this period, the auxiliary switch S_{a1} is turning-off achieving ZVS-ZCS commutation condition. In the time interval between t_3 and t_4, the load current is supplied from L_r and by electric charge stored in C_r in a QR manner. The resonant current in the inductor decreases to zero at time t_4. The inductor current and capacitor voltage for this time interval are

$$i_{Lr}(t) = I_o + i_{cr}(t) = I_o + \frac{V_S}{Z_0}\sin(\omega_o t) \quad (11),$$

$$v_{cr}(t) = -V_s \cos(\omega_o t) \quad (12),$$

where $Z_o = \sqrt{L_r / C_r}$ and $\omega_o = 1/\sqrt{L_r C_r}$. Equation (11) shows that the inductor current only returns to zero if $I_o < V_s / Z_o$, otherwise it commutates with non-zero current flow.

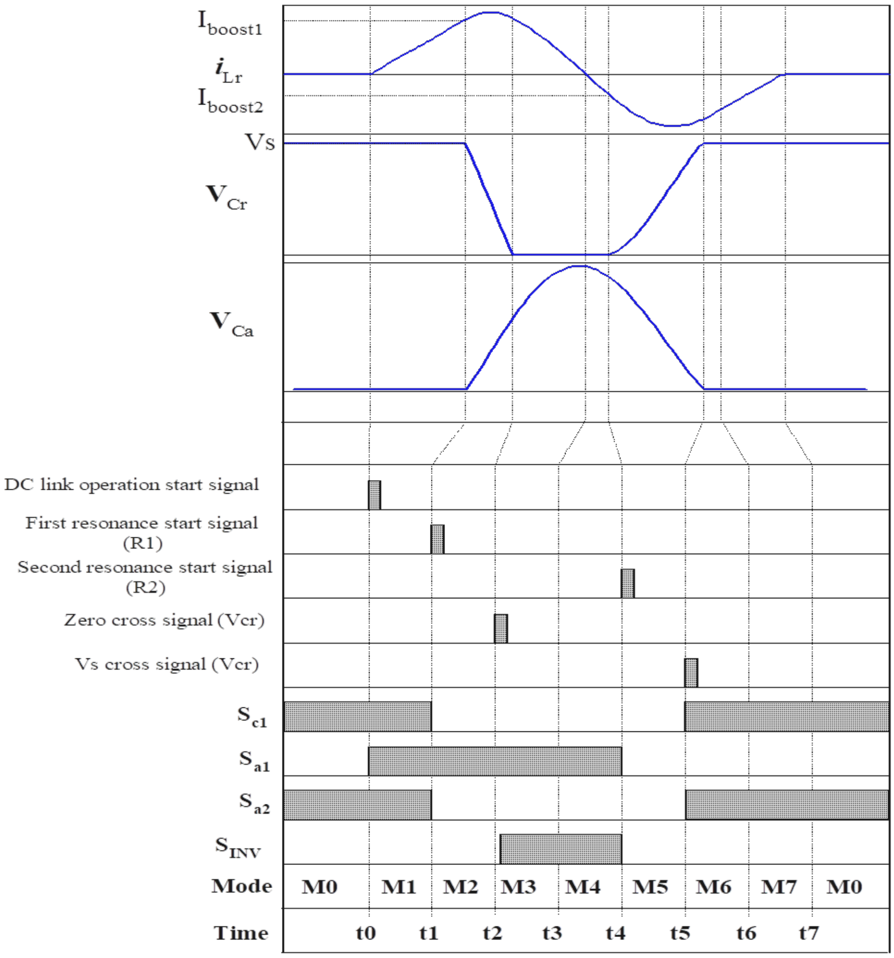

Figure 3: Switching patterns and the operation waveforms of the QR DC link snubber.

Mode 5 (t_4-t_5): As soon as the inductor current i_{Lr} reaches to the second quasi-resonance value I_{boost2}, the switch S_{INV} turns off under ZVS condition, and starting the quasi-resonance formed by L_r, C_r and C_a.

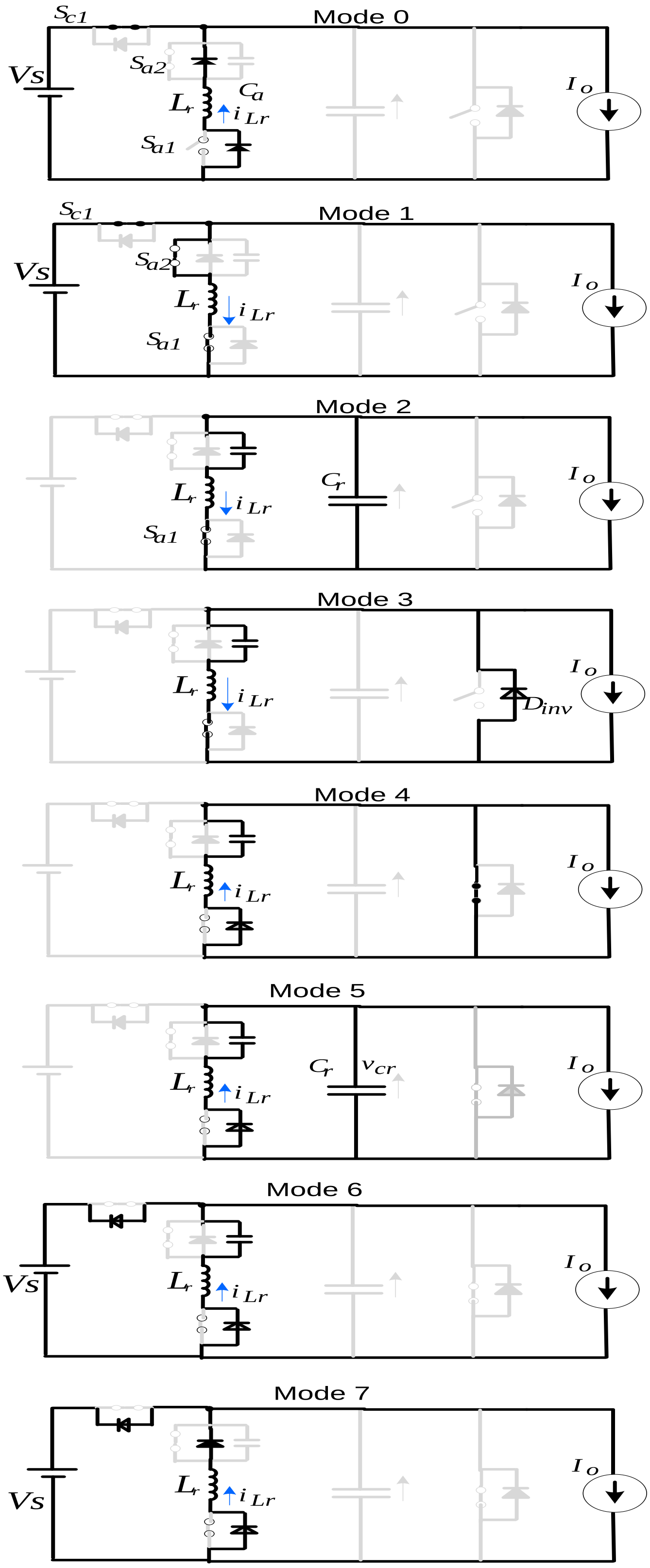

Figure 4: Equivalent circuits and switching mode transitions.

The capacitor voltage V_{cr} *(t)* rises linearly from 0 to *Vs* and is clamped to *Vs*. The corresponding equations in this time interval are expressed as

$$i_{Lr}(t) = I_4 + \frac{V_S + V_0}{Z_0}\sin(\omega_o t) \tag{13}$$

(13),

$$v_{cr}(t_5) = V_s \tag{14}$$

(14),

$$v_{cr}(t) = -V_s \cos(\omega_o t) + V_s \quad (15),$$

where I_4 is the load after the switching state.

Mode 6 (t_5-t_6): The main QR voltage across the capacitor v_{cr} reaches to the dc voltage source voltage V_s. At this time, the diode which is connected to the voltage clamp switch in back-to-back conducts and both the switches S_{c1} and S_{a1} turn on at the ZVS/ZCS condition.

Mode 7 (t_6-t_7): The inductor QR current flows through diode anti-parallel to S_{c1} and regenerated to the DC voltage source V_s. The gate signal of all the semiconductor switches and the operation waveforms for current and voltage of the QR snubber circuit are shown in Figure 3. As soon as the capacitor voltage $v_{cr}(t)$ reaches $-V_o$ at t=t_6, the diode parallel to S_{a2} starts conduction. This interval ends when the switch S_{a1} is closed again to start the next cycle. The duration of this interval is T_7 which is equal to t_6-t_7.

4. Experimental Implementation

The configuration and specifications of the experimental system are shown in Figure 5 and Table 1, respectively. In this system, the operation of the QR DC link snubber of the voltage-fed three-phase inverter is validated, and the conductive noise of the system is measured. Both the on time and off time have about 2 μsec delays. As a result, the switching timing of the main circuit is delayed if the switching pattern indicated in Figure 3 is applied. Therefore, the first QR start signal is used as a trigger signal and the switching timing of the main switches are decided by 74LS123.

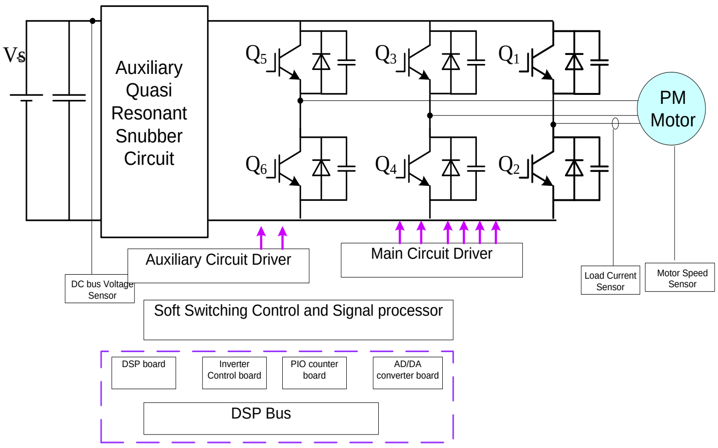

Figure 5: Experimental setup system.

For the conductive noise measurement, the hard and the hard switching are compared under the condition of the same peak load current value. In the experimental system, the operation of resonant DC link snubber of voltage-fed three phase inverter is validated, and conductive noise of the system is measured. Figure 6 indicates waveforms of operation of snubber circuit. The voltage of the main QR capacitor is pulled down to zero voltage and pulled up to the DC bus-line voltage V_s, and all the main inverter switches achieved the ZVS during this DC bus-line notch mode period. Figure 7 indicates the U-phase load current wave.

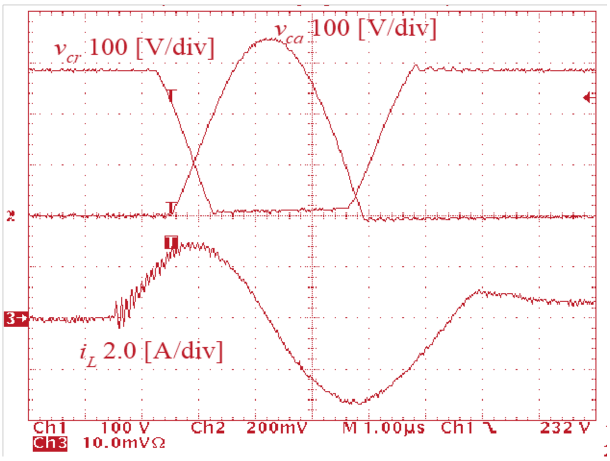

Figure 6: Operation waveforms of QR dc-link snubber circuit.

Table 1: Experimental Parameters.

Power source	DC power source voltage	V_s	280 [V]
Auxiliary resonant snubber circuit	Main resonant capacitor	C_r	10[nF]
	Auxiliary resonant capacitor Cs	C_a	10[nF]
	Resonant inductor	L_r	101[µH]
	Power switches devices IGBT CM75DY-12H	S_c, S_{a1}, S_{a2}	Maximum rate Ic=75[A], Vces=600 [V]
Voltage surge suppression snubber	Voltage clamp capacitor	*Cs*	0.22[mF]
	Snubber diode	*Ds*	USR30P12
	Snubber resistance	*Rs*	20[Ω]
PM motor (BM0230)	Leakage inductance	L_{load}	10[mH]
	Stator resistance	R_{load}	7.5[Ω]
	Number of poles	*P*	8
	Rated current	I_{max}	1.4[A] , rms
Main circuit	Power switching device (PM50RSA060)	$S_{\approx}$ S_{w2}	Maximum rate I_c=50[A], V_{ces}=600[V]
Sampling frequency		*Ts*	10[kHz]

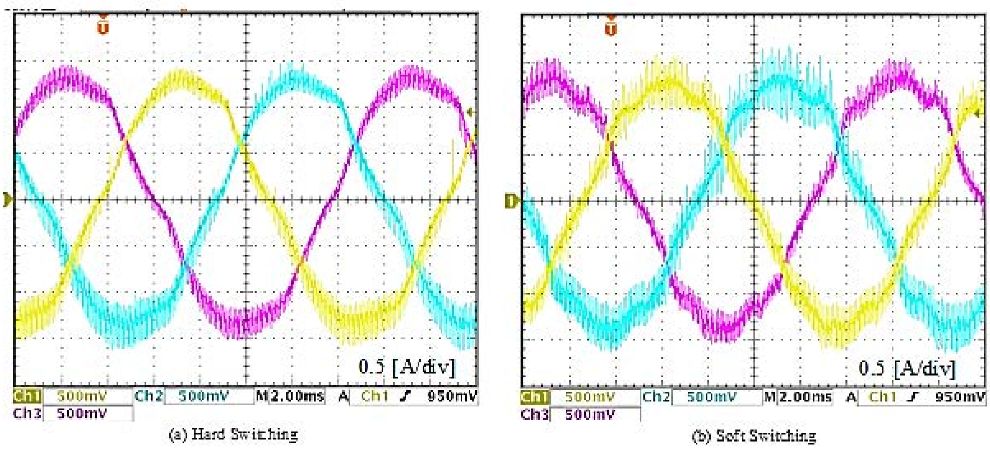

Figure 7: Three-phase load current.

5. Power Loss Analysis

The investigated losses in a motor drive converter are the losses resulting from the power semiconductors switches (IGBTs and Diodes) and the passive circuit components (inductors and capacitors). As well known, the power losses during operation of the power semiconductor devices can be categorized into switching losses and conduction losses. The losses can be estimated where an ideal three-phase sinusoidal Pulse Width Modulated (PWM) voltage is supposed. The distribution of losses calculated under condition of 3-kW output power is illustrated in Figure 8. The efficiencies of ZVS soft-switched and hard-switched inverters are compared as illustrated in Figure 9.

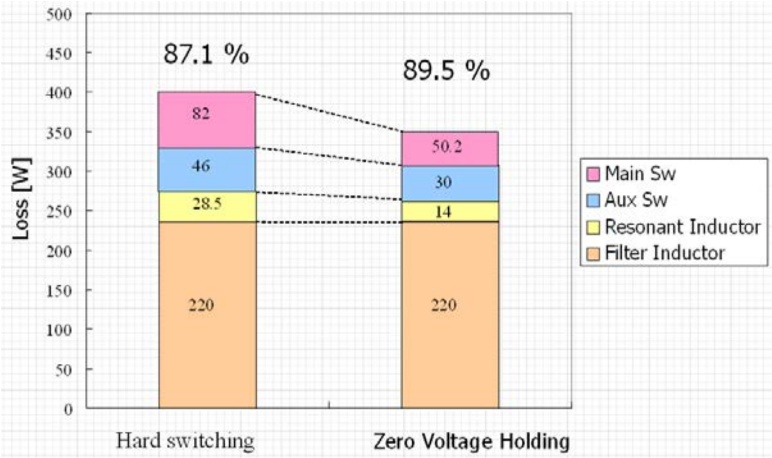

Figure 8. Loss calculation

The losses in the inductor filter are about 220 W. While the resonant inductor losses are 28.5 W and decreased by using soft-switching to 14 W. The losses in the auxiliary switches are reduced from 46 W to 30 W. The losses in the main switches are decreased from 82 W to 50.2 W. However, the total losses are decreased from 367.5 W to about 314 W. The circuit efficiency is improved from 87.1% to 89.5%.

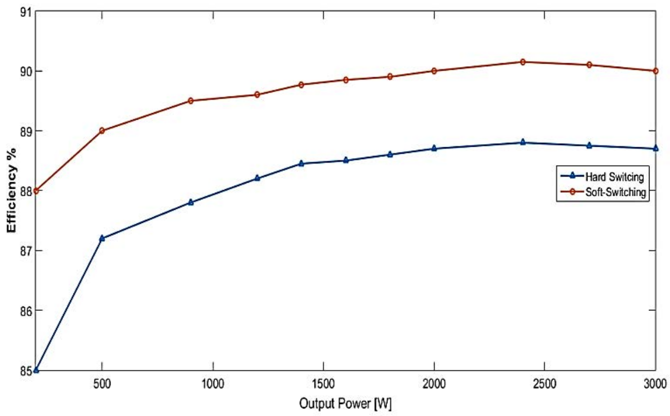

Figure 9: Efficiency curve.

The efficiency is measured using a power analyzer in laboratory. Figure 9 shows that use of soft-switching technique helps to improve the circuit efficiency. For the IGBTs, turning-on and turning-off and on-state conduction losses are deliberated, while the reverse blocking losses are supposed negligible. Likewise, for the diodes, on-state conduction and turning-on switching losses are taken into account, but the turning-on losses are ignored due to a presumed fast diode turning-on process. However, the goal of this clarification is only to provide an idea regarding the losses valuation.

6. Conclusion

A small scale PM motor drives circuit topology of an auxiliary active DC link QR snubber was presented. By using the proposed soft-switching scheme, a good performance of servo motor drive is obtained. The measured and simulated results show that a good performance of soft-switched inverter is obtained. The theory of operation is explained using operation modes and switching equivalent circuits. The experimental waveforms were introduced and discussed for the practical perspective. The results show that the efficiency of is improved using auxiliary switches in the PM motor drive.

7. Availability of Data and Material

Data can be made available by contacting the corresponding author.

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