Journal of King Saud University – Engineering Sciences 32 (2020) 425–431

Contents lists available at ScienceDirect

Journal of King Saud University – Engineering Sciences

journal homepage: www.sciencedirect.com

Original article

Efficient solution of the DC-link hard switching inverter of the PV system

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ARTICLE INFO

Article history:
Received 13 March 2018
Accepted 3 September 2018
Available online 6 September 2018

Keywords:
Resonant dc-link soft switching
Hard switching inverter
Soft switching
Switching losses
Conduction losses

ABSTRACT

Soft switching inverter alleviate and treat the negative impacts resulted from hard switching inverter. It provides many advantages such as low power losses, high efficiency, stress reduction during switching instants, and high reliability and lowering EMI generation. Soft switching is achieved in this paper by adding the LC resonant circuit to the voltage source inverters (VSI). This is the first time to achieve soft switching with the photovoltaic (PV) system. To demonstrate the effectiveness of this technique, the simulation of the PV system is using both switching techniques; the resonant dc-link soft switching inverter and the conventional hard switching inverter; is introduced, analyzed and compared. The total resonant dc-link soft switching losses are reduced dramatically to the half of the total hard switching losses in case of not using soft switching. To validate our work, the detailed comparisons between the proposed topology with another famous one is introduced, analyzed and evaluated. In addition, the resonant dc-link soft switching losses and the hard switching losses of the inverter are estimated. The total resonant dc-link soft switching losses and the total hard switching losses are calculated under similar operating conditions and the conduction losses are kept constant in both switching modes. The simulation results prove the superiority performance of the PV system based on the proposed resonant dc-link soft switching mode compared to the other ones based on the conventional hard switching mode and single transistor resonant dc-link soft switching inverter.

1. Introduction

Renewable energy sources especially solar PV and wind attracted the attention of the majority of the world countries in the last two decades due to its cleanness, availability, less maintenance and friendly to the environment. Both these energy conversion systems require power inverters which have many switching devices such as IGBT and MOSFET. Power inverters applications are increased more and more especially with the massive development of the modern power electronics devices. These power inverters are exposed to hard switching where the voltage or current across the switch is suddenly interrupted. The switch turns on at high voltage and it turns off simultaneously at high current, this leads to the hard switching phenomena. The conventional hard switching inverter has many demerits such as high switching power losses, high devices stresses, low performance and efficiency, and generation of EMI resulting from high *di/dt* and high *dv/dt* due to fast transitions (Erickson and Maksimovic, 2007; Fujii et al., 2006; Ming and Zhou, 2011; Mohan and Undeland, 2007; Shao et al., 2000; Venkataramanan and Divan, 1993).

In order to overcome the negative impacts of the hard switching, many literatures (Chuang et al., 2012; Divan, 1989; Kim et al., 2009; Lu et al., 2011; Shao et al., 2000; Skvarenina, 2001) introduced different techniques of soft switching. Ned Mohan in Mohan and Undeland (2007) implemented the soft switching for dc-dc converter and designed the dc-dc converter under high switching frequency in the range of 100–200 kHz to reduce the converter size, reducing the switching losses, and maintaining high energy efficiency. The merit behind increasing the switching frequency is that, the inductors and capacitors will be small. Hence, high power density and low costs have been achieved. Also, it will improve the power quality through minimizing the harmonics in power converter applications (Divan, 1989; Mishima et al., 2013; Oggier et al., 2011; Skvarenina, 2001). In other words, soft switching can be classified into zero voltage switching (ZVS) and zero

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Peer review under responsibility of King Saud University.

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https://doi.org/10.1016/j.jksues.2018.09.001
1018-3639/

current switching (ZCS) with IGBT or MOSFET power devices (Li and Wolfs, 2008). In Andersen and Alvsten (1995), soft switching on dc-ac inverter based on ZVS is achieved. Whereas, ZVS in the dc–dc conversion stage is implemented using two-inductor boost converter (Wolfs and Li, 2002), a series resonant half bridge converter (Lohner et al., 1996) and a flyback converter as the dc–dc conversion stage cascaded with a current PWM inverter (Martins and Demonti, 2001, 2002). Therefore, soft switching can be implemented in the dc-dc conversion stage and/or in the dc-ac conversion stage. These converters have the ability to remove the switching power losses under high switching frequencies. On the other hand, it demonstrates some benefits compared to conventional hard switching VSI such as high power densities, high efficiencies, and 100% power device utilization (Bellar et al., 1998; Chuang et al., 2012; Divan, 1989; Erickson and Maksimovic, 2007; Mohan and Undeland, 2007; Obdan et al., 2005). Soft switching achieve high reliability due to stresses reduction during switching instants, reduce voltage and current ratings of the devices components, and low di/dt and dv/dt lead to lower voltage spike and EMI emission (Bellar et al., 1998).

Based on the previous two paragraphs, hard switching mode will make the PV system suffering from many problems. By this the authors mean that the power losses of the PV energy conversion system will be increased. Also, the power electronics devices will be stressed due to hard switching hence, the life time of these devices will be decreased. Therefore, the efficiency and the reliability of the PV system will be affected and the performance of the PV system will be bad. In order to achieve a PV system with good performance, balance between technical and economic issues should be taken into consideration. Technical issues include efficiency, reliability and stability. This can be achieved through tracking the maximum power available from the PV system and decreasing the power losses (Srikumar and Saibabu, 2020). Soft switching will participate mainly in the power losses reduction where it nearly removes the switching losses. On the other hand, the economical side includes factors that will save and reduce the total cost such as choosing the best or suitable modules, locations, inverters and dc-dc converters.

In this paper, an efficient solution of the dc-link hard switching inverter for the PV energy conversion system interconnected to the electric utility is proposed. This is the first time to apply soft switching through dc-dc converter (boost converter) of the PV energy conversion system to remove the switching power losses. The boost converter is used to track the MPP available from PV system and the PWM converter is used to convert dc voltage to ac voltage to be connected with electric utility. It introduces a new approach to mitigate the negative impacts resulted from hard switching inverter. These negative impacts include high switching losses due to higher overlap of switch voltage and current. In addition, low efficiency, low reliability due to high stresses during switching instants, high output harmonics and low power density. Also, the output power generation is poor. Soft switching has been done via resonant dc-link inverter under high switching frequency. The efficient performance of the resonant dc-link inverter will be introduced and proved. Finally, the comparisons between the two different techniques, the resonant dc-link soft switching inverter and the hard switching VSI have been presented.

2. Resonant DC-link inverter of grid-connected PV system description

Inverters are power electronic devices that convert direct current or voltage to alternating current or voltage. The whole PV energy system is simulated in Matlab/Simulink. Three-phase inverters are used for high power converter applications. Basically, it consists of three legs each leg has two switches, upper and lower ones, and the three legs are connected to the three-phase load or electric utility as shown in Fig. 1. In the hard switching, the switch turns off simultaneously at full current, and it turns on at full voltage. The switches are exposed to high stresses and high power losses that increase linearly with the switching frequency. EMI is produced due to high *di/dt* and *dv/dt* caused by switching modes. Soft switching inverters with high frequencies lead to minimize the previous shortcomings resulting from the switches modes where the switch voltage and current will be zero at the switching instants, ON and OFF states, respectively (Bellar et al., 1998; Mohan and Undeland, 2007). The switching power losses of the VSI are reduced using two methods. The first method is using snubber circuits with the switches where the snubber circuits shift only the switching losses from the switch to its components and therefore the overall switching power loss doesn't decrease (Liu, 1999; Yaisom et al., 2002). The second method is achieved by applying resonant dc-link soft switching inverter which reduces the switches power losses dramatically.

The resonant dc-link soft switching inverter is formed by adding the LC resonant circuit to the VSI as shown in Fig. 2. The LC resonant circuit makes the input voltage to oscillate where it remains zero for a finite period during the variation instants of the switches, ZVS (Mohan and Undeland, 2007). The current source represents the current drawn by the load which may be represented as a motor, it will include LC filter and contains L_{load} much greater than L_r. Initially, the capacitor is fully discharged and the switch voltage is zero where the switch is turned on. If it is assumed that the switch is ideal, the voltage across the inductor is V_{dc}. so the inductor current starts to increase linearly as (Chuang et al., 2012; Divan, 1989):

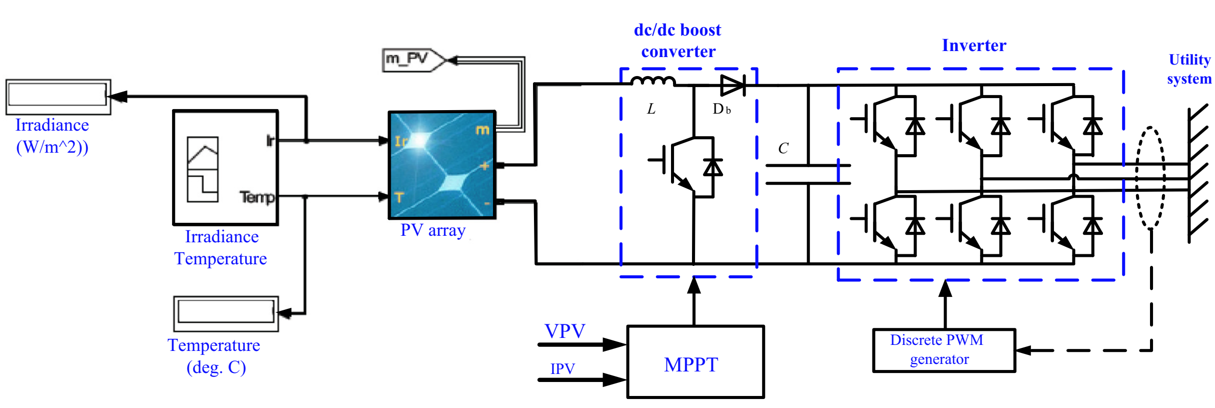


Fig. 1. Grid connected PV energy system.

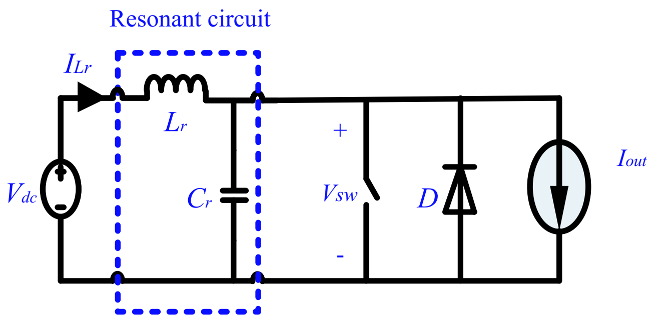


Fig. 2. Equivalent circuit for the resonant dc-link inverter.

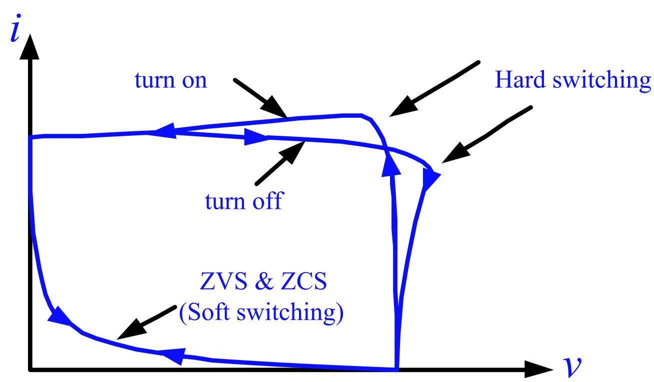


Fig. 3. Hard and soft switching of the power switches.

$$\frac{di_L}{dt} = \frac{v_L}{L} \tag{1}$$

The switch current is equal to the difference between I_{Lr} and I_{out}. V_{sw} will be zero meaning that the switch is on still I_{Lr} becomes equal to I_{out}, at this moment the switch turn off, ZVS. The voltage across the inductor is still positive, hence I_{Lr} continues to increase. At this instant, there is current passing through the capacitor which equals the difference between I_{Lr} and I_{out}. The antiparallel diode conducts and clamps V_c to zero. The LC circuits lead to create oscillation of the dc-link voltage as sinusoidal waveform. Hence, either ZVS or ZCS conditions can be obtained for achieving the soft switching of the power switches and greatly reducing their stress levels and switching losses as shown in Fig. 3.

The capacitor voltage and the inductor current are obtained as follow (Chuang et al., 2012; Divan, 1989):

$$v_c(t) = V_{dc} + e^{-\alpha t}[-V_{dc}\cos\omega t + \omega L\,(I_{Lr0} - I_{out})) * \sin\omega t \tag{2}$$

$$i_L(t) = I_{out} + e^{-\alpha t} * [(I_{Lr0} - I_{out})\cos\omega t + \frac{V_{dc}}{\omega L}\sin\omega t] \tag{3}$$

where

$$\alpha = \tfrac{R}{2L}$$
$$\omega = \sqrt{\omega_0{}^2 - \alpha^2}$$
$$\omega_0 = \tfrac{1}{\sqrt{LC}}$$

In this analysis, it is assumed α is much lower than ω. In order to achieve ZVS, it is necessary that the capacitor voltage should return finally to zero.

3. Hard switching and soft switching losses calculations

3.1. Hard switching losses

The total hard switching losses are shown as follow (He and Mohan, 1991; Krogemann, 1997; kumar Pattnaik and Mahapatra, 2010):

$$P_{tot}(HSI) = P_{tot-con} + P_{tot-sw} \tag{4}$$

3.1.1. Conduction losses

The total conduction losses, $P_{tot\text{-}con}$ of the switches are shown (Krogemann, 1997; kumar Pattnaik and Mahapatra, 2010; Mohan and Undeland, 2007):

$$P_{tot-con} = 6\,(P_{q-con} + P_{d-con}) \tag{5}$$

where the conduction losses in the IGBT($P_{q\text{-}con}$), the conduction losses in the diode ($P_{d\text{-}con}$) can be obtained as follow:

$$P_{q-con} = V_q \cdot I_{q-avg} + R_q \cdot I^2_{q-rms} \tag{5.a}$$

$$P_{d-con} = V_d \cdot I_{d-avg} + R_d \cdot I^2_{d-rms} \tag{5.b}$$

The parameters, V_q, R_q, V_d, and R_d are given in data sheets. The average and root mean square currents of the IGBT (I_q) and diode (I_d) are estimated as follow (Krogemann, 1997; kumar Pattnaik and Mahapatra, 2010; Mohan and Undeland, 2007):

$$I_{q-avg} = I_{o(p)}\left[\frac{1}{2\Pi} + \frac{m_a\cos\varphi}{8}\right] \tag{5.c}$$

$$I_{d-avg} = I_{o(p)}\left[\frac{1}{2\Pi} - \frac{m_a\cos\varphi}{8}\right] \tag{5.d}$$

$$I_{q-rms} = I_{o(p)}\sqrt{\frac{1}{8} + \frac{m_a\cos\varphi}{3\prod}} \tag{5.e}$$

$$I_{d-rms} = I_{o(p)}\sqrt{\frac{1}{8} - \frac{m_a\cos\varphi}{3\prod}} \tag{5.f}$$

3.1.2. Switching losses

The hard switching losses are equivalent to IGBT turn on, turn off losses and the diode reverse recovery losses which are calculated as shown (Krogemann, 1997; kumar Pattnaik and Mahapatra, 2010):

$$P_{tot-sw} = 6f_s \cdot \frac{E_{tot}}{\Pi} \tag{6}$$

where

$$E_{tot} = K_g \cdot (E_{on} + E_{off})\frac{V_s}{V_{test}} \cdot \frac{I_{o(p)}}{I_{test}} \tag{6.a}$$

Data sheets provide E_{on} and E_{off} which are the turn on and turn off switching losses respectively per IGBT pulse.

3.2. Soft switching losses

The total resonant dc-link soft switching losses are equal to the summation of the conduction losses in the main IGBT and diodes ($P_{main\text{-}con}$), switching losses in the inverter devices ($P_{main\text{-}sw}$), and the losses in the resonant inductor (P_{Lr}) and are given as follow (Krogemann, 1997; kumar Pattnaik and Mahapatra, 2010; Mohan and Undeland, 2007):

$$P_{tot} = P_{main-con} + P_{main-sw} + P_{L_r} \tag{7}$$

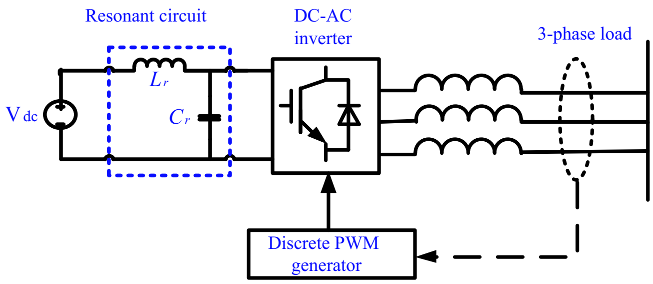


Fig. 4. Circuit diagram of the proposed resonant dc-link for three-phase inverter. (a) Hard switching, (b) Soft switching.

where

$$P_{main-con} = 6\left(P_{q-con} + P_{d-con}\right) \tag{7.a}$$

$$P_{main-sw} = 6\frac{f_r}{2}E_{off}\left[I_{o(p)}\right] \tag{7.b}$$

$$P_{L_r} = \frac{Z_r}{Q}I_r^2 \tag{7.c}$$

Turn off switching losses, E_{off} can be obtained from:

$$E_{off}\left[I_{o(p)}\right] = Z_r I_{o(p)}^2 \beta(1-\beta)\left(\frac{1}{\omega} - \frac{\sin\omega t_{tail}}{\omega^2 t_{tail}}\right) + \left(V_s\beta I_{o(p)} + \frac{\beta^2 I_{o(p)}^2 L_r}{t_{tail}}\right)\left[\frac{t_{tail}}{2} - \frac{(1-\cos\omega t_{tail})}{\omega^2 t_{tail}}\right]$$

After calculating the turn off energy (E_{off}), the turn off switching losses can be found by multiplying it by the resonant frequency, f_r.

4. Proposed simulation system

The simulated model of resonant dc-link of the three-phase inverter using Matlab/Simulink is shown in Fig. 4. The universal bridge block shown in Fig. 4 represents a three-phase VSI that consists of six switches connected in a bridge block. The power switches and inverter configuration are selected from the Simulink library. The bridge block allows simulation of inverters using natural commutation of power electronic switches such as diodes or thyristors and forced-commutation switches such as GTO, IGBT, and MOSFET. The IGBT inverter is controlled by a PI regulator in order to maintain a 1 pu voltage, 380 V_{rms}–60 Hz, at the load terminals.

The simulation of the PV energy conversion system has been carried out using Matlab/Simulink. The model contains the dc source connected to the utility grid or the three-phase load through dc-ac voltage source inverter. The dc voltage can be obtained from directly PV system or from wind turbine followed by three-phase bridge rectifier. The control of whole system in modeling software contains the voltage regulator followed by the discrete Pulse Width Modulation (PWM) generator. This discrete PWM block generates pulses for carrier-based PWM, self-commutated IGBTs, GTOs, or MOSFETs bridges.

5. Results and discussions

The hard switching and soft switching technique are presented where the power inverter is evaluated before and after adding the

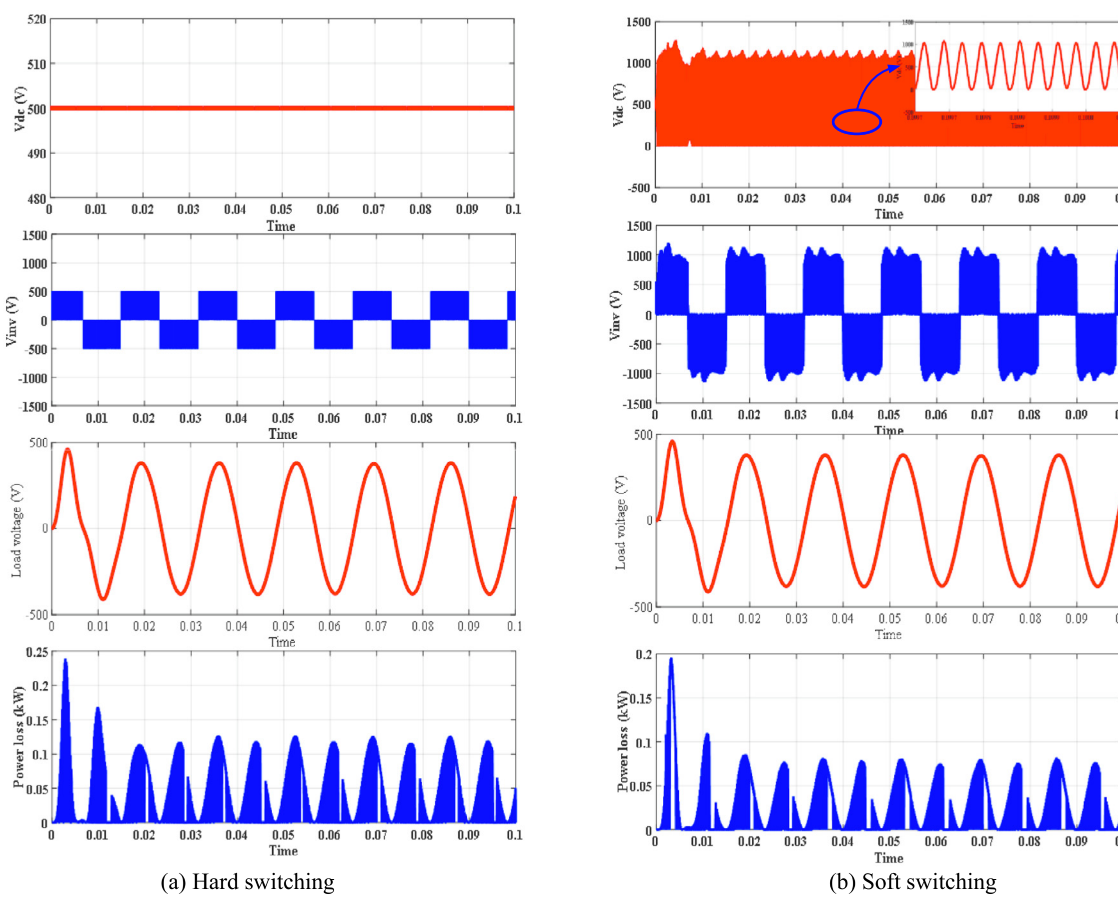
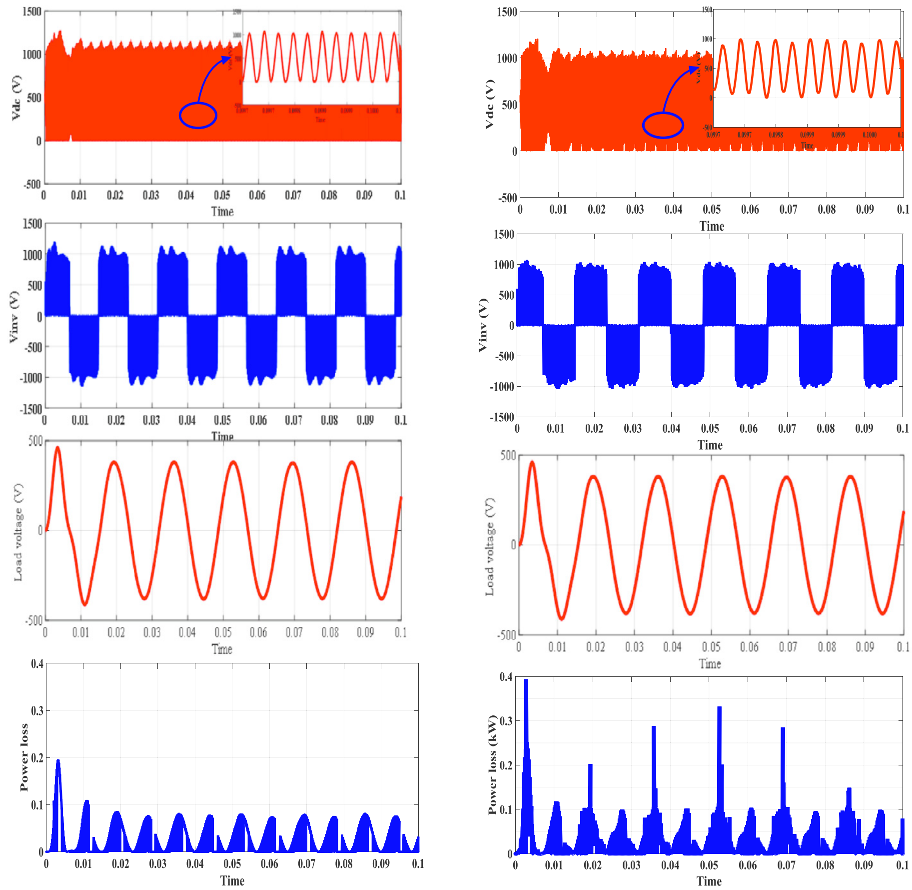


Fig. 5. Typical waveforms of V_{dc}, $V_{L\text{-}inv}$, $V_{L\text{-}load}$ and the switching power losses: (a) before adding LC resonant circuit, (b) after adding LC resonant circuit.



(a) Proposed topology (b) Single transistor resonant dc-link (Divan, 1989)

Fig. 6. Comparison between the waveforms of our proposed topology and the topology used in Divan (1989).

Table 1
Calculation of total losses for the hard and soft switching.

Switching type	Losses type (W)			
	Conduction losses	Switching losses	Resonant inductor losses	Total losses
Hard switching	108.8	177.6 (at 5 kHz)	–	286.4
		246.3 (at 10 kHz)	–	355.1
		315.1 (at15 kHz)	–	423.9
Single transistor resonant dc-link inverter (Divan, 1989)	126	4	45	175
Resonant dc–link soft switching inverter	108.8	2.9	11.8	123.5

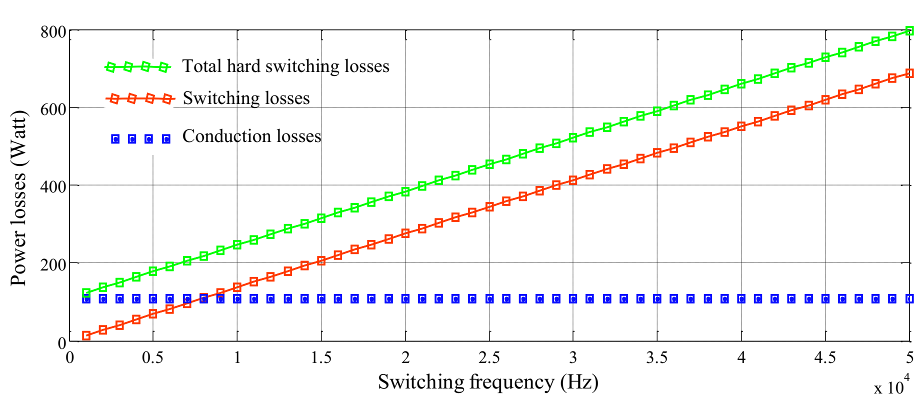


Fig. 7. Power losses of hard switching as a function of switching frequency.

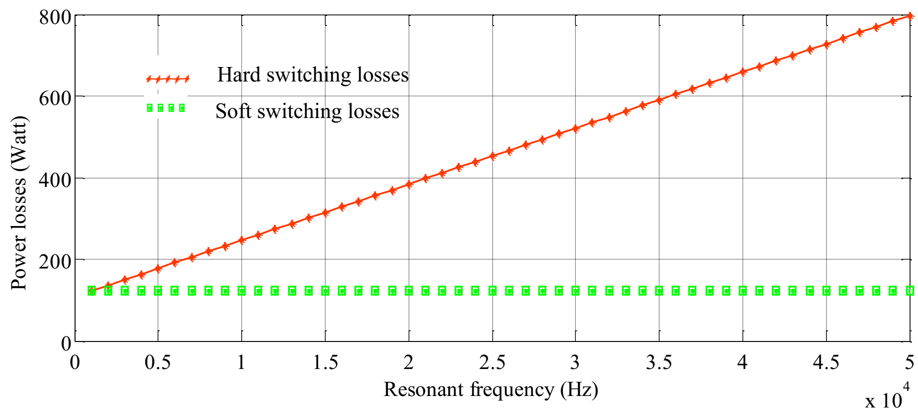


Fig. 8. Variation of total hard and soft switching losses with respect to frequency.

LC resonant circuit to the VSI. Fig. 5(a) shows waveforms for V_{dc}, $V_{L\text{-}inv}$, $V_{L\text{-}load}$, and the switching power losses of the conventional dc-ac inverter in the case of hard switching inverter. On the other hand, Fig. 5(b) shows all waveforms for the soft switching inverter after adding LC resonant circuit. It is observed that the dc voltage is constant value (500 V) in the case of the hard switching while in the case of soft switching there are sinusoidal oscillations of the dc voltage which is doubled (1000 V); ZVS and ZCS are achieved. The voltage remains zero for a finite period during the variation instants of the inverter switches either for ZVS or ZCS conditions. It is concluded that, the switching power losses are higher compared to soft switching as shown in Fig. 5. Soft switching has been achieved using resonant dc-link inverter (RDCLI) where the LC resonant circuit was added to the VSI. It reduces the switching power losses considerably at least by the half compared to conventional hard switching inverter. The inverter voltage take the form of square wave which are converted to three-phase pure sinusoidal after the LC filter representing the load line voltage as shown in Fig. 5.

To validate our results, the proposed solution of the hard switching through adding LC resonant circuit is compared with the topology used in Divan (1989); single transistor resonant dc-link inverter. The whole simulation results of our proposed solution using LC resonant circuit and that using single transistor resonant dc link inverter in Divan (1989) are shown in Fig. 6 in left hand side and right hand side, respectively. According to Divan (1989), 4.5-kW VSI was simulated and the inverter switching frequency was 18 kHz under 3-phase load. $L = 65\ \mu H$ and $C = 1$ pF without snubber circuits and these values are used in our proposed system for our proposed topology.

For a comparison, the total resonant dc-link soft switching losses and the total hard switching losses are also calculated theoretically using the same switching devices under the identical operating conditions for our topology and the single transistor resonant dc-link inverter topology in Divan (1989). The calculated results are collected in Table 1. It can be observed that, the switching power losses are linearly proportional to the switching frequency f_{sw}. In addition, the switching losses for the our resonant dc-link inverter and that in Divan (1989) are reduced considerably, while the conduction losses in the main switches still the same. It is observed that the total losses of our proposed topology is lower than the proposed topology in Divan (1989). In general, the soft switching losses are sharply reduced compared to the hard switching losses under the same conditions in addition to the resonant dc-link inverter has a reasonable reduction in the total power losses.

On the other hand, Matlab code program is implemented based on the equations mentioned previously in Section 4 to plot the total hard switching versus the switching frequency in addition to plot the soft switching losses versus the resonant frequency. Fig. 7 shows that as the switching frequency increases, as the hard switching losses increase, while the conduction losses are kept constant with respect to different values of the switching frequency. Briefly, the total hard switching losses are affected and increased sharply with the increasing of the switching frequency while the total resonant dc-link soft switching losses remains constant whatever the switching frequency value is, as shown in Fig. 8.

6. Conclusions

Based on the simulation results, the total hard switching power losses are higher compared to the total losses associated with soft switching. The reason behind that is the fixed value of the dc voltage under the hard switching while; there is a sinusoidal oscillation of the dc voltage under soft switching. The voltage and current during soft switching remains zero for a finite time during the switching instants either for ZVS or ZCS conditions. Resonant dc-link soft switching is affectively achieved by adding the LC resonant circuit to the VSI for this purpose. The total resonant dc-link soft switching losses are reduced considerably to the half or lower of the total hard switching losses. Therefore, soft switching can improve the efficiency and reliability of the PV energy conversion system. On the other hand, the total hard switching losses and the total resonant dc-link soft switching losses are calculated theoretically under the same operating conditions. It is concluded that the conduction losses are kept constant in both switching modes. whereas, the total hard switching losses are affected and increased sharply with the increasing of the switching frequency while the total soft switching losses does not affected by the switching frequency value.

Acknowledgment

The authors extend their appreciation to the Deanship of Scientific Research, King Saud University for funding this work through the Undergraduate Research Support Program, project no. (URSP-3-17-42).

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