



## Comparison of Control Techniques for Series Resonant Converter

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### Abstract

There are many different derivatives of variable and fixed frequency switching control techniques used in control of load resonant converters. In this study; among these techniques frequency modulation (FM), phase shift modulation (PSM) and pulse density modulation (PDM) are applied separately to series resonant converter (SRC). The techniques are examined and compared in many respects. An experimental setup is built, which consists of a 400W converter, a control circuit and a resistive load to verify theoretical studies. The converter is controlled by FM, PSM and PDM separately for 120 kHz basic operating frequency and different output currents. Experimental results are compared in terms of efficiency, output voltage ripple, soft switching, switch voltage, ease of application and hardware. The comparison results are presented. Thus, effect of each technique on the operating parameters of the converter is revealed. Moreover, it is also observed that FM has better performance than the other two techniques in many aspects

## 1. INTRODUCTION

Efficiency of load resonant converters is affected by input voltage and output current levels of different applications in which they are used. Another factor that has an effect on the efficiency is techniques used in control of these converters [1]. The techniques can be divided into variable frequency switching and fixed frequency switching, which have different applications, for instance FM and PSM. While FM is the variable frequency switching control technique, PSM is the fixed frequency switching control technique. The both are traditional methods [2]. PDM is one of the fixed frequency switching techniques, which is frequently used in control of resonant inverters as well as DC-DC converters [3, 4].

Output power control with FM is performed by changing switching frequency ( $f_s$ ). In the FM, when it is desired to decrease the output power while operating above the resonance frequency ( $f_r$ ), it is necessary to increase the switching frequency. However, with increasing switching frequency, switching losses and electromagnetic interference (EMI) also increase. Therefore, changing the switching frequency for the output power control is the disadvantage for the FM. In addition, when operating below the resonance frequency, filter design becomes difficult due to the changing switching frequency [5-8]. Despite these disadvantages, its simple structure and easy applicability are the advantages of FM [9, 10].

Changing the duty ratio of the inverter voltage, which defines the effective value of the inverter voltage, performs the power control in PSM. As long as the resonance current is lagging with respect to the inverter voltage, the switches are turned on under soft switching conditions. However as the duty ratio of inverter voltage is decreased, the resonance current is leading with respect to the inverter voltage. As a result, soft switching conditions of some switches are disappeared and the switching losses increase [10-12]. The disadvantage of PSM is that the soft switching conditions of some switches are disappeared as the load current decreases. Operation at fixed switching frequency is the advantage of PSM.

PDM control can be divided into two groups as regular and irregular, the power control is performed by deleting some of switching pulses [13]. PDM is especially used in induction heating applications [14-16]. Main reason for this is that the system response does not need to be fast since the work piece temperature controlled in this application does not change rapidly. Therefore, fast output response is not required unlike DC-DC converters. Disadvantages of the regular PDM are that the varying of damping time depending on the quality factor of the resonance current causes the fluctuations in the output power and the peak value of the resonance current is much bigger than the other two techniques, especially with the decreasing load current [17,18]. In order to eliminate these disadvantages of the regular PDM method, the irregular PDM is recommended. By maintaining the oscillation of the resonance current with the irregular PDM, phase locking loop continues to operate and the changes in the resonance current are reduced. Thus, the fluctuations in the power transferred to the load are reduced. Amount of sub harmonics also decreases with the irregular PDM. However, this method requires complex and large logic circuits or memory elements to obtain gate signals of the power switches [19-22]. In the regular PDM, the control signals of the power switches can be obtained by simple logic circuits [23].

There are also hybrid applications of FM, PSM and PDM used for the power control of the load resonant converter [24-26]. In these applications, the power control is performed with more than one technique by benefiting from the advantages of each technique for different load conditions. Thus, the decreasing converter efficiency is prevented, especially in light loads. However, as a result of using more than one technique together, complexity, application difficulty and components of the control unit increase.

SRCs have a suitable structure for half and full-bridge applications. The full-bridge, which is more suitable for application of different control techniques, is preferred in this study. Because of the advantages of operating above the resonance frequency at high frequencies, the switching frequency of the full-bridge SRC is selected above the resonance frequency and MOSFETs are used as power switches. A 16-bit dsPIC33FJ16GS502 digital signal controller (DSC) is used to execute the control algorithm, generate the control signals of the switches and digitize the feedback information.

## 2. CONTROL OF THE FULL-BRIDGE SERIES RESONANT CONVERTERS

The isolated full-bridge SRC and control circuit used in experimental studies are shown in Figure 1. A lot of different control techniques such as FM, PSM and PDM are used to control the converter [3, 27, 28].

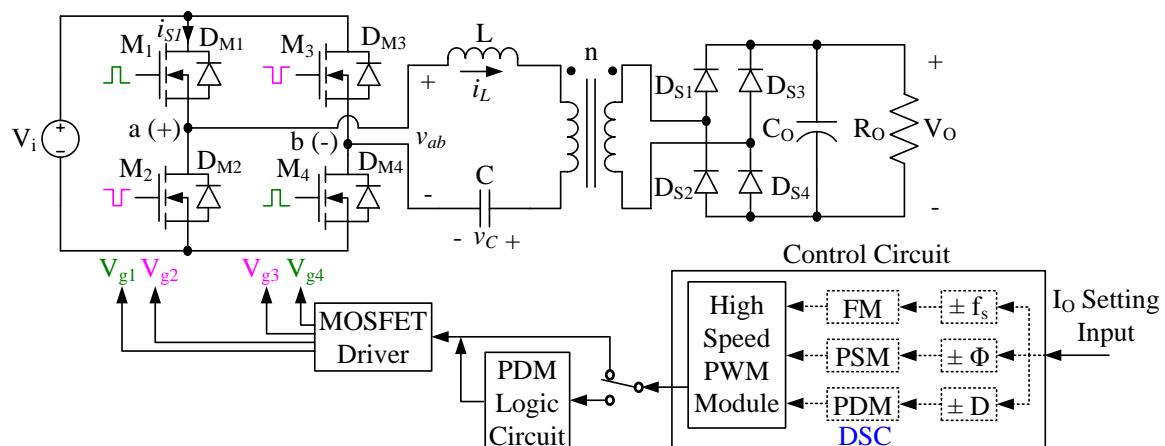


Figure 1. The isolated full-bridge SRC and control circuit

The classification of these techniques is given in the following sections.

### 2.1. Variable Frequency Control

Different derivatives of the variable frequency switching control technique are as follows:

- Frequency modulation

- Average current
- Capacitor voltage
- Diode conduction angle
- Optimal curve control

Among these techniques, FM is the most preferred technique because of its simple structure and easy application [5]. Gate signals  $V_{g1-g4}$ , theoretical waveforms of the inverter voltage  $v_{ab}$  and current  $i_L$  of FM controlled converter are given in Figure 2a.

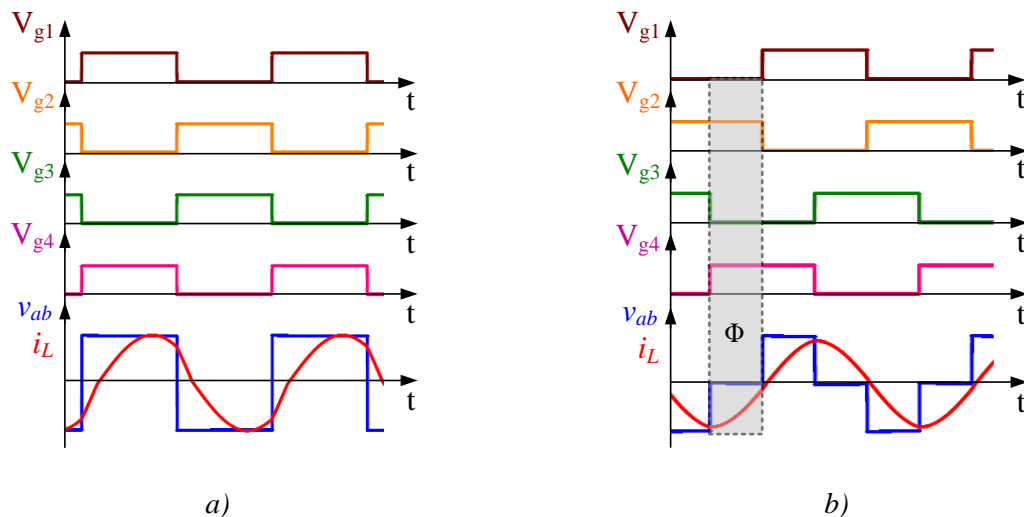


Figure 2. Waveforms of FM and PSM controlled converter, a) FM, b) PSM

While changing the switching frequency that is the control variable of this technique controls the load current, the duty ratio and peak value of the inverter voltage remain constant. In addition, the converter has four different operating intervals in steady-state conditions. Since the current is lagging in all of these operating intervals, the power switches are turned off under hard switching while they are turned on under zero voltage switching (ZVS).

## 2.2. Fixed Frequency Switching Control

Although the fixed frequency switching technique has different derivatives [1, 2], the control variables in these techniques differ in contrast to the variable frequency control technique. Among these techniques; PSM and PDM are frequently used in the control of resonant converters and resonant inverters, respectively.

- Phase shift modulation
- Asymmetric phase shift modulation
- Asymmetric duty ratio
- Unipolar voltage cancellation
- Secondary party
- Pulse density modulation

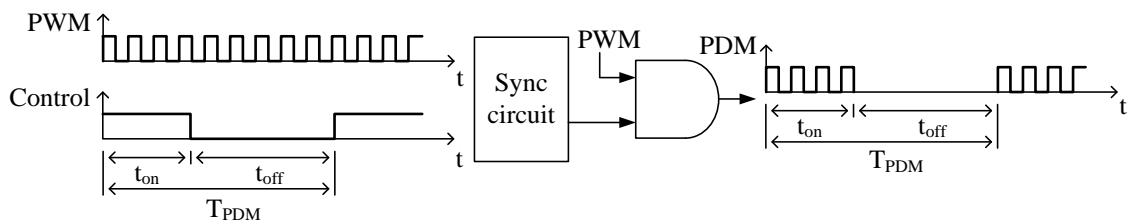
### 2.2.1. Phase Shift Control

Generally PSM is preferred to avoid the variable frequency switching for the power control and to operate at the fixed switching frequency [10-12]. The power control in PSM is accomplished by varying the duty ratio of the inverter voltage. Gate signals of the power switches, inverter voltage and current waveforms of PSM controlled converter are given in Figure 2b. The duty ratio of the inverter voltage is obtained by changing the angle  $\Phi$ , which is the phase difference between the gate signals of the diagonal power switches. Since the angle  $\Phi$  is the control variable, it is changed from 0 to 180 degrees to control the output current. In PSM, the output current decreases as the phase angle  $\Phi$  increases. The three different

operating states occur with the decrease of the output current of PSM controlled converter [27, 28]. In one of these states, all of the power switches are turned on under ZVS conditions and the current is lagging. This operating state is preferred because of the higher efficiency, especially in applications where MOSFET is used as the power switch at high frequencies [27].

**2.2.2. Pulse Density Modulation Control**

In a PDM, the switching losses can be reduced by operating at the resonance frequency or at a frequency close to the resonance frequency. The regular PDM is used in the experimental studies due to its simple control circuit structure and easy applicability. The application of the regular PDM is given in Figure 3. PWM pulses and the control signal are applied to the synchronization circuit to synchronize control and PWM signals and then the synchronization circuit output and PWM pulses are applied to AND gate to determine number of PWM pulses used to drive the power switch.

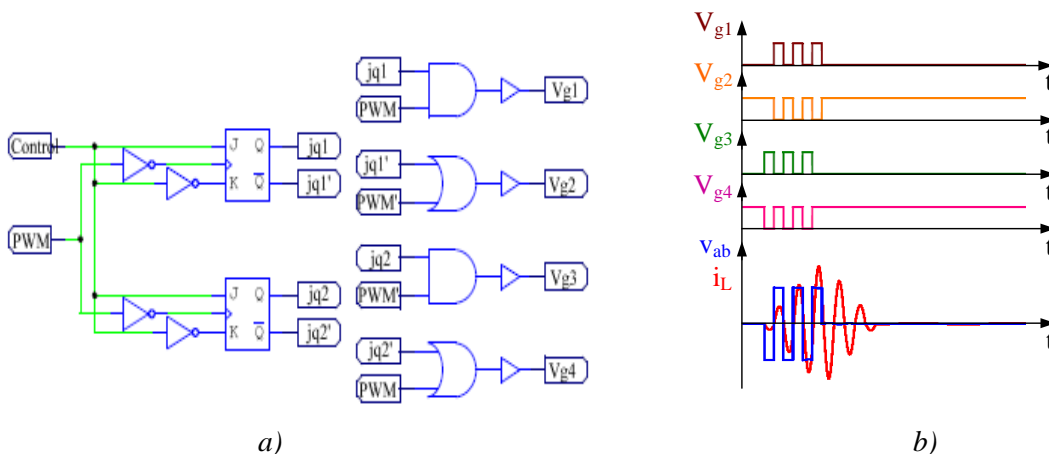


**Figure 3.** The generation of the regular PDM signals

PDM control is accomplished by changing the duty ratio  $D$  of the control signal given in Equation 1. Hence, the control variable is the duty ratio of the control signal.

$$D = \frac{t_{on}}{T_{PDM}} \tag{1}$$

In FM and PSM, gate signals of the power switches can be obtained with analog integrated circuits or programmable circuit elements such as microcontrollers [29-31]. The logic circuit or memory elements are required to obtain gate signals of the power switches in the regular or irregular PDM [18-22]. The logic control circuit of the regular PDM used in experimental studies is given in Figure 4a.



**Figure 4.** The logic circuit used to obtain the regular PDM signals and the waveforms of regular PDM controlled converter, a) logic circuit, b) the waveforms

Gate signals of the power switches, waveforms of the inverter voltage and current for PDM controlled converter are given in Figure 4b. For operating above the resonance frequency,  $t_{on}$  interval operation of PDM controlled converter is same as FM controlled converter. However, by keeping the power switches

$M_2$  and  $M_4$  in conduction throughout  $t_{off}$ , the inverter voltage becomes zero. Therefore, there is no energy transfer from the source to the load at  $t_{off}$  interval.

### 3. TEST RESULTS OF DIFFERENT CONTROL TECHNIQUES FOR RESISTIVE LOAD

In this study for purpose of comparison of three different control techniques named as FM, PSM and PDM, the experimental set up is built as given in Figure 5. The converter and control circuit on the same board used to control the output current separately with three different techniques are given in Figure 6.

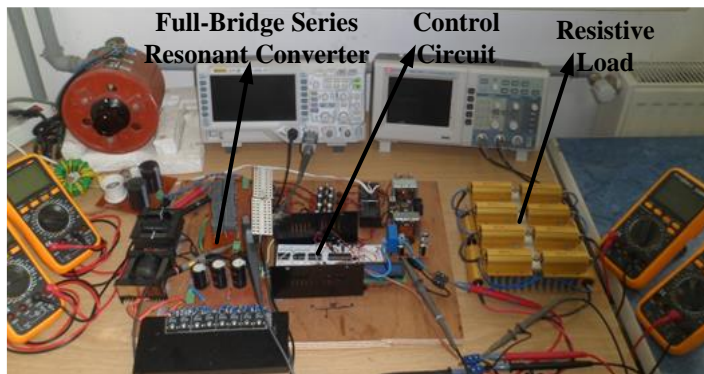


Figure 5. The experimental setup

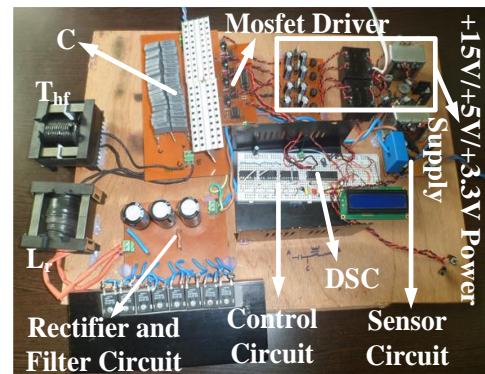


Figure 6. The converter circuit

The parameters of the converter are as given in Table 1.

Table 1. The parameters of the converter

$V_i=200$ V	$n=18:4$	$L=191$ $\mu$ H	$C=10$ nF	$f_r=115$ kHz	$R_o=3.33$ $\Omega$
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The output voltage, current and power of the converter for 120 kHz fixed operating frequency are 36.4 V, 10.8 A and 393.12 W, respectively. Gate signals of the power switches, inverter voltage and current waveforms of the converter are given in Figure 7 for 120 kHz.

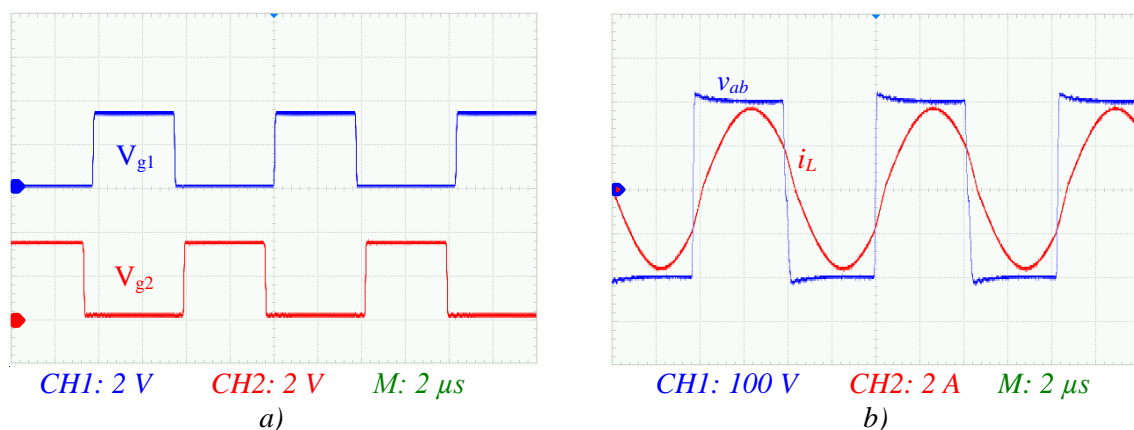
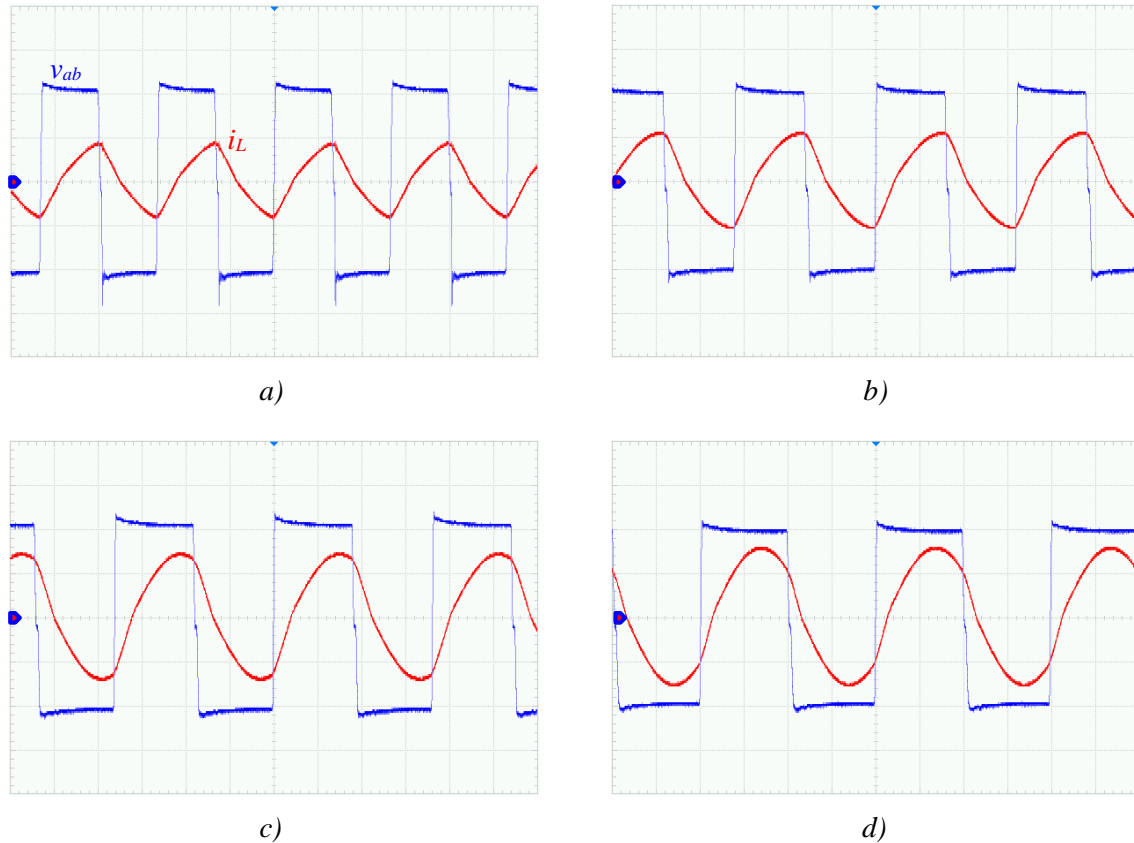


Figure 7. Gate signals of the power switches, inverter voltage and current for 120 kHz, a) gate signals of the power switches, b) the inverter voltage and current

In order to compare the techniques, the load current of the converter is controlled separately by each control technique in 1 A intervals from 4 A to 10 A. The input current ( $I_i$ ), input voltage ( $V_i$ ), inverter current ( $i_L$ ) and voltage ( $v_{ab}$ ), output current ( $I_o$ ), output voltage ( $V_o$ ) and output voltage ripple ( $\Delta V_o$ ) are measured and recorded for each determined output current value. While  $I_i$ ,  $V_i$ ,  $I_o$  and  $V_o$  are measured by a digital multimeter,  $i_L$  is measured by a Tektronix 011-0105-00 AC current probe.

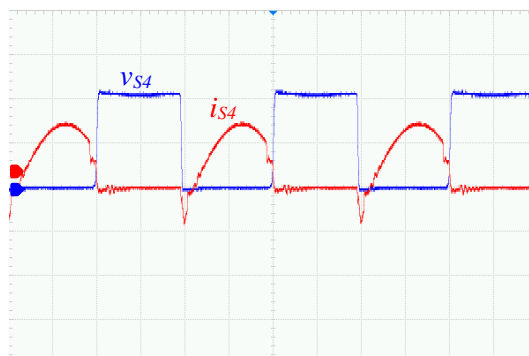
### 3.1. Frequency Controlled Converter

Gate signals of the power switches of FM controlled converter are obtained by using a pair speed PWM module and two output pins of DSC. The output current is controlled from 4 A to 10 A by changing the switching frequency of the converter between 187.97 kHz and 125.63 kHz. The waveforms of the inverter voltage and current for these output currents are given in Figure 8.



**Figure 8.** The inverter voltage and current of FM controlled converter for the different output currents (CH1: 100 V, CH2: 2 A and M: 2  $\mu$ s), a) 4 A, b) 6 A, c) 8 A, d) 10 A

An increase of 62.34 kHz is required in the switching frequency to reduce the output current from 10 A to 4 A in FM controlled converter. While the power switches are turned on under ZVS conditions, they are turned off under hard switching. The voltage ( $v_{S4}$ ) and current ( $i_{S4}$ ) of the switch  $M_4$  are given in Figure 9 for 10 A.



**Figure 9.** The voltage ( $v_{S4}$ ) and current ( $i_{S4}$ ) of  $M_4$  for 10 A (CH1: 100 V, CH2: 2 A and M: 2  $\mu$ s)



The results summarizing the operation of FM controlled converter for the different output currents are given in Table 2.

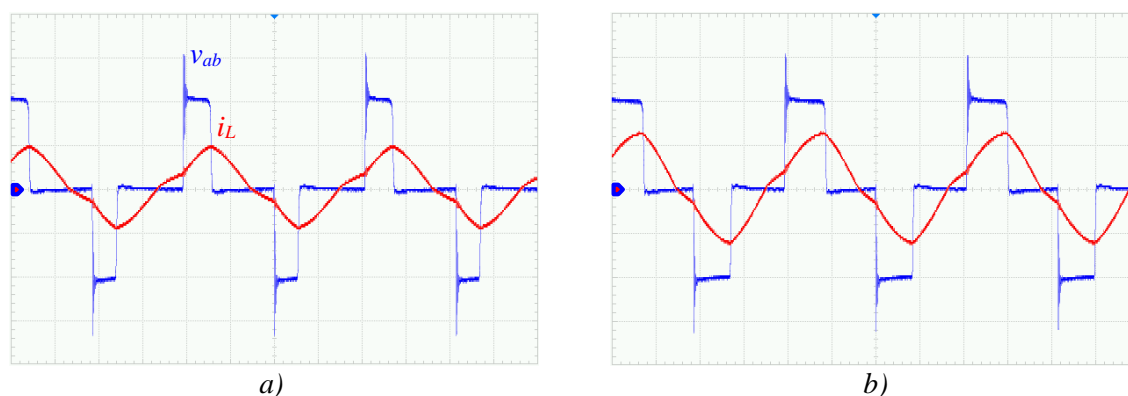
**Table 2.** Operation parameters of FM controlled converter

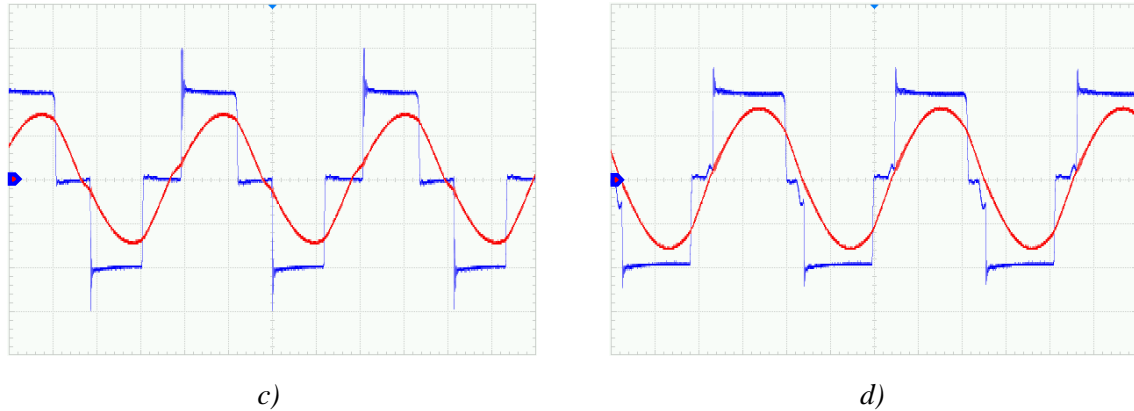
$V_i$ (V)	$I_i$ (A)	$V_o$ (V)	$I_o$ (A)	Efficiency (%)	$\Delta V_o/V_o$ (%)	$I_{Lm}$ (A)	Frequency (kHz)	Switch Stresses (V)
200	0.372	14.10	4.03	76.37	4.25	1.85	187.97	280
200	0.524	17.00	5.01	81.26	3.82	1.97	171.23	260
200	0.715	20.30	6.03	85.6	3.44	2.2	156.25	230
200	0.957	23.50	7.02	86.19	3.19	2.48	146.2	230
200	1.236	26.90	8.02	87.27	3.71	2.92	138.12	230
200	1.561	30.30	9.03	87.63	4.62	3.08	130.89	220
200	1.905	33.50	10.02	88.1	5.97	3.2	125.63	220

The efficiency is obtained by dividing the output power ( $V_o I_o$ ) by the input power ( $V_i I_i$ ) and it decreases as the switching frequency increases in FM, as seen in Table 2. The voltage stresses across the switch increase as the output current decreases. However, ZVS is guaranteed from 10 A to 4 A as the converter operates above the resonance frequency.

### 3.2. Phase Shift Controlled Converter

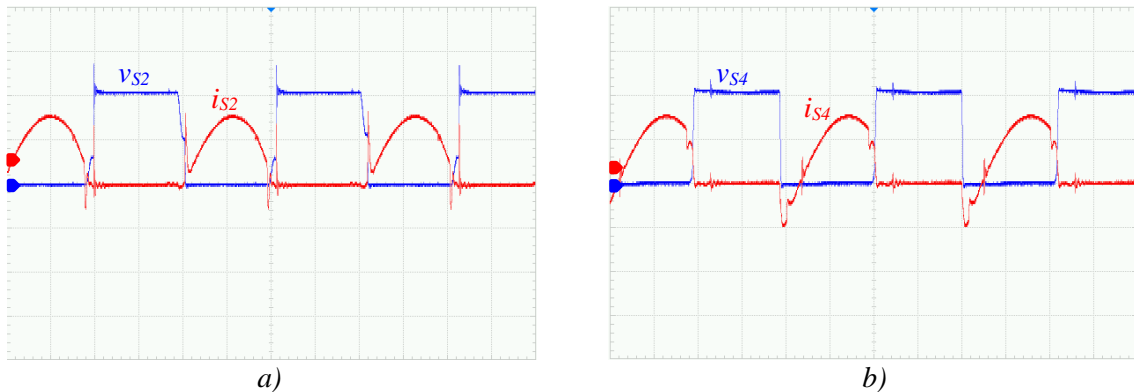
Gate signals of the power switches of PSM controlled converter are obtained by using two pair speed PWM module and four output pins of DSC. The inverter voltage and current of the converter whose switching frequency is 120 kHz and output current is controlled by PSM from 4 A to 10 A, are given in Figure 10.





**Figure 10.** The inverter voltage and current of PSM controlled converter for the different output currents (CH1: 100 V, CH2: 2 A and M: 2  $\mu$ s), a) 4 A, b) 6 A, c) 8 A, d) 10 A

Since the phase difference ( $\Phi$ ) increases with the decreasing output current in PSM controlled converter, the lagging current becomes leading with respect to the inverter voltage. As can be seen from the voltage and current waveforms of  $M_2$  and  $M_4$  switches given in Figure 11 for 10 A, while the power switches on the left arm of the full-bridge are leading, the power switches on the right arm of the full-bridge are lagging. As a result, ZVS conditions for the power switches on the left arm are disappeared. The switches are turned off under zero current switching conditions and turned on under hard switching. Moreover, the switch stresses increase with increasing the phase difference. On the other hand, while the switches on the right arm are turned on under ZVS, they are turned off under hard switching.



**Figure 11.** The voltage and current of  $M_2$  and  $M_4$  for 10 A (CH1: 100 V, CH2: 2 A and M: 2  $\mu$ s), a) the voltage and current of  $M_2$ , b) the voltage and current of  $M_4$

The results summarizing the operation of PSM controlled converter for the different output currents are given in Table 3.

**Table 3.** Operation parameters of PSM controlled converter

$V_i$ (V)	$I_i$ (A)	$V_o$ (V)	$I_o$ (A)	Efficiency (%)	$\Delta V_o / V_o$ (%)	$I_{Lm}$ (A)	$\Phi$ Phase Angle ( $^\circ$ )	Switch Stresses (V)
200	0.415	14.1	4.04	68.631	3.9	1.95	118.77	340
200	0.625	17.5	5.04	70.56	4	2.4	105.84	320
200	0.855	20.9	6.02	73.578	4.7	2.6	92.31	320
200	1.13	24.4	7.03	75.899	4.9	2.9	77.77	320

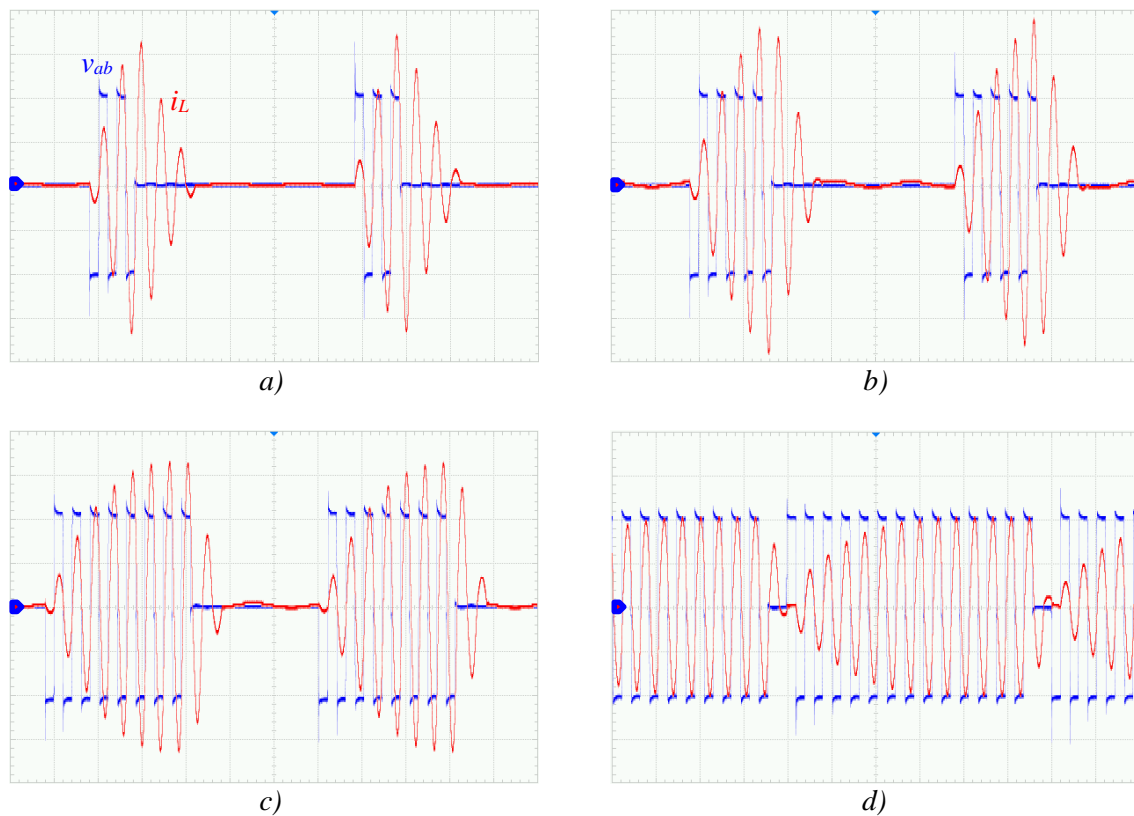


200	1.449	28.2	8.05	78.333	5.1	3.02	62.21	300
200	1.72	31.2	9.05	82.081	5.9	3.46	47.47	310
200	1.982	33.8	10.06	85.779	6.8	3.3	30.52	260

As the output current decreases from 10 A in PSM, the switch stresses increase and the efficiency decreases due to disappeared ZVS conditions of the switches ( $M_1$ ,  $M_2$ ) on the left arm.

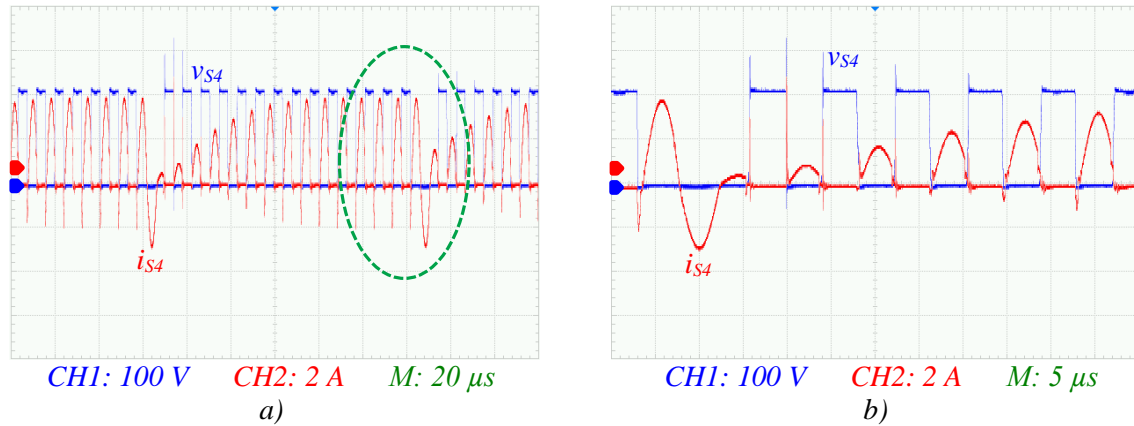
### 3.3. Pulse Density Controlled Converter

The frequency of PDM control signal is 8.22 kHz and the switching frequency is 120 kHz. Two pair speed PWM modules and four output pins of DSC and the additional logic circuitry are used to obtain gate signals of the power switches. The inverter voltage and current waveforms of PDM controlled converter for different output currents are given in Figure 12.



**Figure 12.** The inverter voltage and current of PDM controlled converter for the different output currents (CH1: 100 V, CH2: 2 A and M: 20  $\mu$ s), a) 4 A, b) 6 A, c) 8 A, d) 10 A

Although the switching frequency is selected above the resonance frequency to guarantee ZVS, in the first three cycles of the duty period of PDM, the current is not lagging and so soft switching conditions are disappeared. Therefore, the voltage stress on the ends of the power switches increases. The voltage and current waveforms of the switch  $M_4$  are given in Figure 13 for 10 A. The zoomed version of the part shown with dashed lines in Figure 13a is given in Figure 13b.



**Figure 13.** The voltage and current of  $M_4$  for 10 A, a) the voltage and current of  $M_4$ , b) the zoomed voltage and current of  $M_4$

The results summarizing the operation of PDM controlled converter for the different output currents are given in Table 4.

**Table 4.** Operation parameters of PDM controlled converter

$V_i$ (V)	$I_i$ (A)	$V_o$ (V)	$I_o$ (A)	Efficiency (%)	$\Delta V_o / V_o$ (%)	$I_{Lm}$ (A)	Duty Ratio (D)	Switch Stresses (V)
200	0.397	13.60	4.02	68.86	6.6	7	0.16	330
200	0.580	17.00	5.02	73.57	5.8	8	0.22	340
200	0.800	20.50	6.05	77.52	6.8	7.6	0.3	300
200	1.060	23.80	7.03	78.92	6.3	7.6	0.39	335
200	1.333	27.20	8.03	81.93	6	6.7	0.53	300
200	1.610	30.50	9.04	85.63	5.9	5.2	0.68	300
200	1.930	33.80	10.02	87.74	6.2	4.2	0.93	310

The peak value of the current of PDM controlled converter is approximately three times higher than FM and PSM, especially for low output currents.

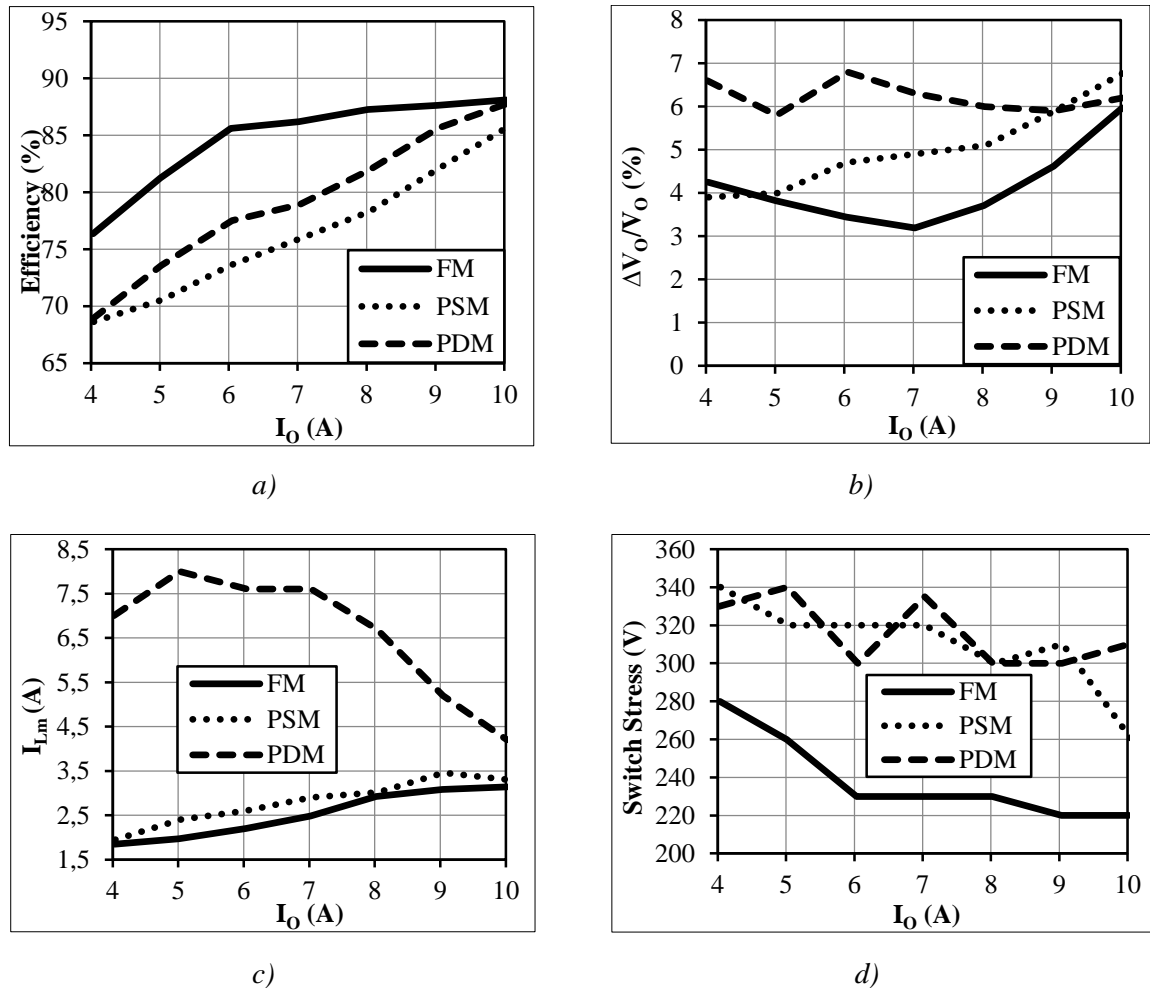
### 3.4. Comparison of The Control Techniques

The efficiency, output voltage ripple, current peak value and switch voltage curves versus the output current of the converter controlled separately by three techniques from 4 A to 10 A are given in Figure 14.

The results obtained from the studies and the curves in Figure 14 are presented comparatively as follows.

- While the highest efficiency is obtained with FM, the technique with the lowest converter efficiency is PSM.
- The technique with the lowest output voltage ripple is FM.
- While FM is the technique with the lowest peak value of the current, it is much higher in PDM compared to FM and PSM.
- The switch voltage stresses of FM controlled converter are lower compared to PSM and PDM controlled converter.
- In FM, the switches are turned on with ZVS in a wide range of the output current. In PDM, while ZVS conditions cannot be satisfied in the first cycles of the control signal, the switches are turned on under ZVS conditions in the following cycles. When the current is leading in PSM, ZVS conditions are disappeared for the two switches on the left arm.

- While FM is the simplest and easiest technique for implementation, PDM is the most difficult one.
- Among the techniques, while FM has the least hardware, PDM has the most hardware because it requires the additional logic circuits other than DSC.
- In terms of the power control, PDM has disadvantageous according to the other two techniques because the resolution of the output power depends on the frequency of the control signal and audible sounds are produced when the frequency of the control signal is selected below 20 kHz.



**Figure 14.** The efficiency, output voltage ripple, current peak value and switch voltage curves versus the output current, a) efficiency, b) output voltage ripple c) current peak value, d) switch voltage stresses

The summary of the examinations and comparisons for the three techniques is given in Table 5.

**Table 5.** Comparison of FM, PSM and PDM

Comparison Futures	Control technique		
	FM	PSM	PDM
Application ease	Simple	Medium	Difficult
Efficiency	High	Low	Low
Hardware structure	Simple	Medium	Complex
Switch voltage	Low	High	High
Soft switching	Moderate	Poor	Moderate
Output voltage ripple	Low	High	High
Resonance current	Low	Medium	High
Operating frequency	Variable	Fixed	Fixed
Dynamic response	Fast	Fast	Slow

As can be seen from Table 5, there is no control technique that meets the positive aspects of all comparison parameters.

#### 4. CONCLUSIONS

In the present study, full-bridge SRC, one of the basic applications of load resonant converters, is designed and built to compare FM, PSM and PDM control techniques. The converter is individually controlled by each of these techniques for different output currents. Except for the additional logic circuit of the PDM, the control of the converter by FM, PSM and PDM is performed via the low-cost DSC. As a result of the control processes repeated with each technique for different output currents, it is observed that these techniques affect the efficiency, the ripple level of the output voltage, the output response speed, the operation under soft switching conditions, the operating frequency, the power control and power switches selection of the converter. The advantages and disadvantages of these techniques, which are compared in many ways, are also determined. Consequently, although FM performs the power control by varying the switching frequency in a wide range, it is more advantageous than PSM and PDM in many ways. In future studies, the hybrid techniques combining the advantages of each technique can be used to control the converter and compared with FM, PSM and PDM techniques.

#### ACKNOWLEDGMENTS

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