# Modeling, Analysis and Control of Different DC-DC Converter Topologies for Photovoltaic Emulator

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**ABSTRACT**

This paper presents the modeling, analysis and control of different DC-DC converter topologies to emulate the photovoltaic (PV) system. A PV emulator is basically a DC-DC converter having same electrical characteristics that of solar PV panel. The emulator helps to achieve real characteristics of PV system in a better way in an environment where using actual PV systems can produce inconsistent results due to variation in weather conditions. The paper describes different types of DC-DC converters like buck, Resonant and Quasi Resonant Converter. The complete system is modelled in MATLAB® Simulink SimPowerSystem software package. The Simulation results obtained from the MATLAB® Simulink SimPowerSystem software package for different topologies under steady and dynamic conditions are analyzed and presented. An evaluation table is also presented at the end of the paper, presenting the effectiveness of each topology.



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## 1. INTRODUCTION

Fast depletion of fossil fuels like oil, natural gas, coal etc. has made the society/researchers/industries to look for cheap and efficient renewable energy options. Moreover the pollution caused by the burning/ consumption of fossil fuels in power stations, automotive vehicles etc. has led the society and researchers to think on the environmental lines. Energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment is defined as renewable energy. Solar energy is a good example of renewable energy as it repeats day after day [1], [2]. Solar energy is being seen as one of the best renewable source of energy specialty in disconnected areas and it is becoming a popular solution to target energy problems in disconnected areas. Moreover, PV panels also finds application in independent systems for the production of electricity, such as solar home systems (SHS), street lighting, community facilities, etc. in isolated/ disconnected areas [3].

Power obtained from solar array depends upon solar insolation, climate etc. [4]. Hence, all the research and development activities required in the areas of solar energy requires a variable, stable and repeatable PV source for design and testing. Hence a PV generator emulator is required and its main function is to reproduce the I–V curve of a practical PV panel. The development of the simulator was initiated/needed for the testing of PV applications such as three phase grid connected inverters or MPPT charge controllers as shown in Figure 1. In Figure 1, a DC-DC converter is used as solar PV emulator. The input is taken from a DC supply/source. The output of the PV emulator is given to the three phase grid connected inverter under test. Initially these tests were initially conducted on physical/real PV arrays, but many issues like changing weather etc. are associated with these types of tests [5]. There are many types of solar PV panels available in the market, and it is uneconomical to buy all of these for testing to find the right product in terms of efficiency. A PV emulator is handy here as it can give the characteristics of all panels at different temperature and varying weather conditions, thus helping in the correct selection of real PV panel suitable to the particular requirement/ weather conditions. Simulation of a solar panel under various irradiances and temperatures is done using the mathematical model approach [6], [7].

In Photovoltaic systems, switched power DC-DC converters are widely used to transform power between one voltages to other and also mainly used in Maximum Power Point Tracker (MPPT) [8]. DC-DC converter has property of variable resistance which plays an important role to emulate solar I-V characteristics and its respective P-V curves of PV array. A well designed solar PV emulator should have the following two features: 1) It should predict nearly same static I-V characteristics of real solar arrays and panel under various weather condition and load conditions. 2) It should be able to give satisfactory result under partial shading condition with more than one peak and step [9]. The DC/DC converter when designed properly can precisely describe the voltage-current and voltage-power characteristics of PV cell/array [10].

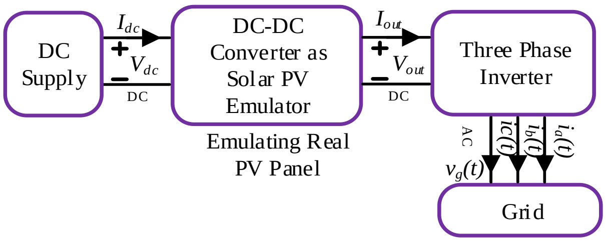


Figure 1. PV emulator connection to a grid connected 3 phase inverter

The PV Simulator Simulation using Buck Converter with analysis using bode diagram is presented in [11]. Many authors have contributed to the small-signal modeling of LCC resonant topology. A small-signal model for LCC resonant converter with LC filter has been well explored for high-frequency applications. Dynamic modeling of LCC resonant topology with capacitive output filter for high-power applications has also been demonstrated by the authors in [12-13]. A new topology for Quasi-square-wave converters has been developed in 1988, and its detailed analysis and modeling is available in literature [14]. With all these research available, but still a comparative evaluation of the above topologies as a PV emulator is missing in the literature, and hence presented in this paper.

The paper is organized as follows: buck converter based PV emulator is explained in section 2. LLC Resonant Converter based PV emulator and Quasi Resonant Buck Converter based PV emulator are presented in sections 3 and 4 respectively. Simulation results are presented and discussed in section 5 and the conclusions in section 6.

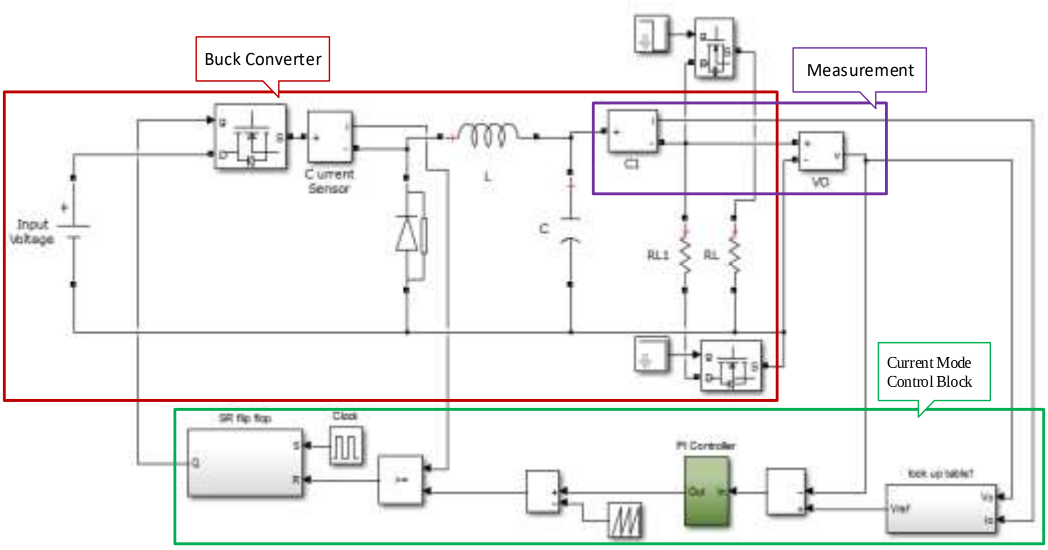


Figure 2. Simulink block diagram of current mode control of buck converter

## 2. BUCK CONVERTER BASED PV EMULATOR

Basic model of the emulator using current mode buck converter is shown in Figure 2. The point of intersection of slope of the (1/R) and I-V characteristics will be the operating voltage and current as shown in the control strategy of the simulator in Figure 3. The output current and output voltage is sensed and then its corresponding resistance can be calculated and then goes to the look up table which creates the reference voltage. The reference voltage is then compared with the output voltage of the model and then goes to the compensator which generates reference current. Switch current is compared with reference current, when switch current reaches reference current then switch is turned off and it is again switch on with the help of SR flip flop.

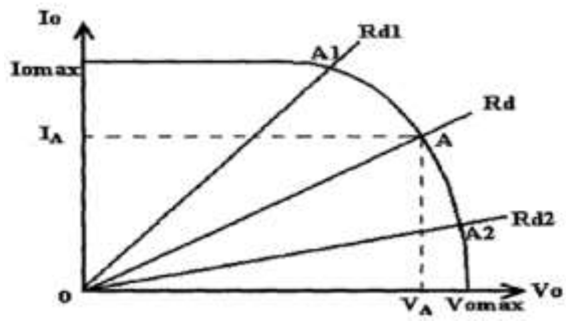


Figure 3. Control strategy of the simulator

## 3. LLC RESONANT CONVERTER BASED PV EMULATOR

PV emulator can be implemented using LLC resonant converter as shown in Figure 4. These types of resonant converter can be operated under zero-voltage switching (ZVS) for the high voltage side switch and zero-current switching (ZCS) of the rectifier diodes for the low voltage side when designed properly. The output impedance of the resonant converter can be regulated from zero to infinite without serial or shunt resistor with the frequency modulation control. Therefore, this type of inverter has significant higher than conventional PWM converter for this application. Voltage gain of the LLC resonant converter is given by equation (1).

$$|M_V(\omega)| = \left|\frac{V_o}{V_{in}}\right| = \frac{1}{2n\{\sqrt{(1+A)^2[1-(\omega_L/\omega)^2]^2+(1/Q_L)^2((\omega/\omega_L)(A/1+A))-(\omega_L/\omega))^2}\}} \quad (1)$$

Where,

$$A = \frac{L_r}{L_m} \quad , \quad \omega_L = 2\pi f_L = \frac{1}{\sqrt{(L_r+L_m)*C_r}} \quad \text{and} \quad Q_L = R_i \cdot \omega_L \cdot C_r$$

$$\omega_L = 2\pi f_L = \frac{1}{\sqrt{L_r*C_r}}$$

## 4. QUASI RESONANT BUCK CONVERTER BASED PV EMULATOR

Zero voltage switching can be obtained when capacitor is connected parallel across switch and zero current switching is obtained when an inductor is connected in series with the switch. Circuit diagram of Quasi resonant buck converter is shown in Figure 5. Regulation of the output voltage is achieved by changing the effective duty cycle, performed by varying the switching frequency of the switch. Thus, changing the effective on-time of the MOSFET in a ZVS design. The foundation of this conversion is simply the volt-second product equating of the input and output. It is somehow identical to that of Pulse width power conversion, and mostly not like those of its electrical dual of energy transfer system, the zero current switched converters.

Regulation of the output voltage is accomplished by adjusting the effective duty cycle, performed by varying the conversion frequency. This changes the effective on-time in a ZVS design. The foundation of this conversion is simply the volt-second product equating of the input and output. It is virtually identical to that of square wave power conversion, and vastly unlike the energy transfer system of its electrical dual, the zero current switched converters.

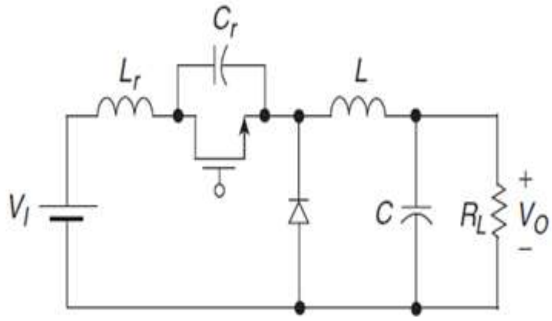


Figure 5. Circuit diagram of quasi resonant buck converter

During the ZVS switch off-time, the L-C tank circuit resonates. Output voltage can be regulated by varying its switching frequency. the voltage across the switch start resonating \from zero to its peak, and back down again to zero. At this point the switch can again be switched on, and lossless zero voltage switching is achieved. Because, the resonant tank discharges the output capacitance of the MOSFET switch (Coss), it do not contribute to power loss dissipated in the switch. Therefore, the MOSFET transition losses become zero regardless of circuit parameter i.e. operating frequency and input voltage. Therefore, it helps in improving the efficiency of the resonant converter. It also helps in decreasing heat losses associated with the MOSFET. This property of resonant converter makes zero voltage switching a suitable for high frequency, high voltage converter designs. Moreover, the gate drive requirements also reduced significantly in a ZVS design due to the lack of the gate to drain (Miller) charge, which is deleted when V& I equals zero.

$$V_{INmax} = V_{INmin} = V_{IN} = 30\ volt \tag{2}$$

$$V_{DSmax} = V_{INmax}(1 + I_{Omax}/I_{Omin}) \tag{3}$$

From equation 2 and 3, Choosing $V_{DSmax}$ to be 6 times more than $V_{IN}$ & $I_{Omax}$=4 amp
$I_{Omin}$ will be .8 amp to achieve zero voltage switching.
A resonant tank period frequency of $f_R$=500 KHz will be used
Then $Z_R=V_{INmax}/I_{Omin}$ = 30/.8=37.5 ohm
L_R=$Z_R/\omega_R$=37.5/2Π*50000 = 11.9 µH
$C_R=1/Z_R\ \omega_R$ = 8.45 nF

## 5. SIMULATION RESULTS AND DISCUSSION

Simulation is done in MATLAB® Simulink environment. The parameters used for buck, LLC resonant, quasi resonant buck converters are listed in Table 1, Table 2 and Table 3 respectively.The output voltage is 0-21 Volts, and output current is 0-4 amperes. The percentage ripple in output voltage and current is kept below 1%. Switching frequency is kept to about 100 kHz. Resonant impedance, inductance and capacitance has been calculated for quasi resonant converter and reported in the Table 3 as 75 ohm, 23.8µH and 4.225 nF respectively.

Table 1. Simulation Parameters of Buck Converter

| Simulation Set up Parameters | Rating |
|---|---|
| Input voltage | 30 Volts |
| Output voltage | 0-21 volts |
| Output current | 0 -4 Amp |
| Switching frequency | 100 kHz |
| Percentage ripple in current | less than 1% |
| Percentage ripple in voltage | less than 1% |
| Inductance of the converter (L) | 12 mH |
| Capacitance of the converter (C) | 2.2mf |

Table 2. Simulation Parameters of LLC Resonant Converter

| Simulation Set up Parameters | Rating |
|---|---|
| Input voltage | 400 Volts |
| Output voltage | 0-21 volts |
| Output current | 0 -4 Amp |
| Maximum power | 66 Watts |
| Resonant frequency | 100 kHz |
| Percentage ripple in current | Less than 1% |
| Percentage ripple in voltage | Less than 1% |

Table 3. Simulation Parameters of Quasi Resonant Buck Converter

| Simulation Set up Parameters | Rating |
|---|---|
| Output voltage | 0-21 volts |
| Output current | 0 -4 Amp |
| Switching frequency | 80-120 kHz |
| Percentage ripple in current | less than 1% |
| Percentage ripple in voltage | less than 1% |
| Output Inductance of the converter (L) | 1 mH |
| Output Capacitance of the converter (C) | 1 mf |
| Resonant impedance (Zr) | 75 ohm |
| Resonant inductance (Lr) | 23.8μH |
| Resonant capacitance (Cr) | 4.225 nF |
| Output min current ($I_{omin}$) | 0.4 A |

Figure 6 and 7 shows output voltage and current of the buck converter respectively. The Load is changed at 5ms and 10ms and the buck converter is controlled via current controller. Figure 6 and 7 shows the dynamics of the converter system also.

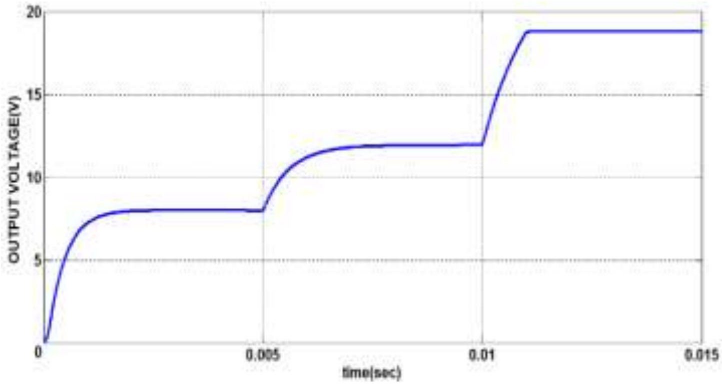


Figure 6. Output voltage of buck converter

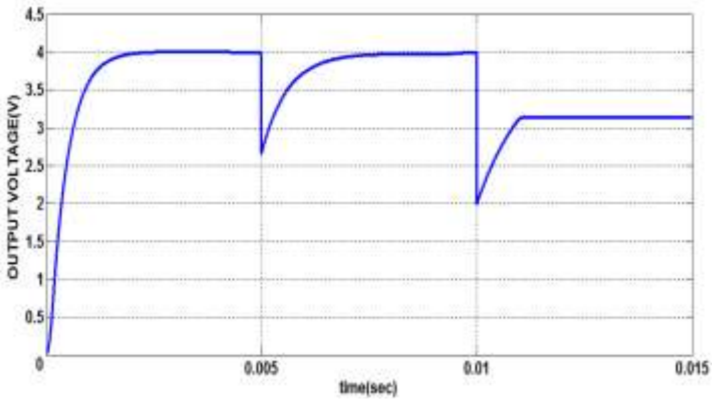


Figure 7. Output current of buck converter

Figure 8 and 9 shows the frequency response of output voltage gain with different Q factor and differnt inductor ratios respeectively. Figure 10 shows resonant current and magnetizing current for maximum power, whereas Figure 11 shows diode current for the same case. It can be seen that diode is turning off with ZCS (zero current switching). Hence, there will not be any spike in the secondary diode current which increases overall efficiency. Figure 12 shows output voltage at maximum power.

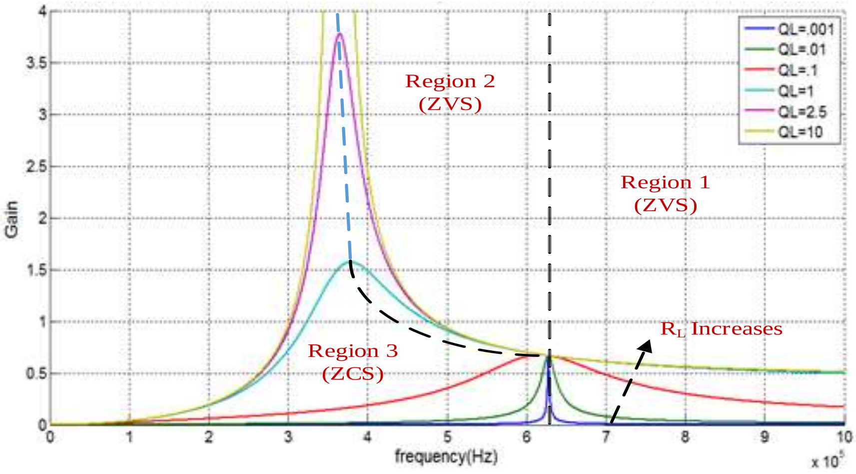


Figure 8. Frequency response of output voltage gain of the LLC resonant converter

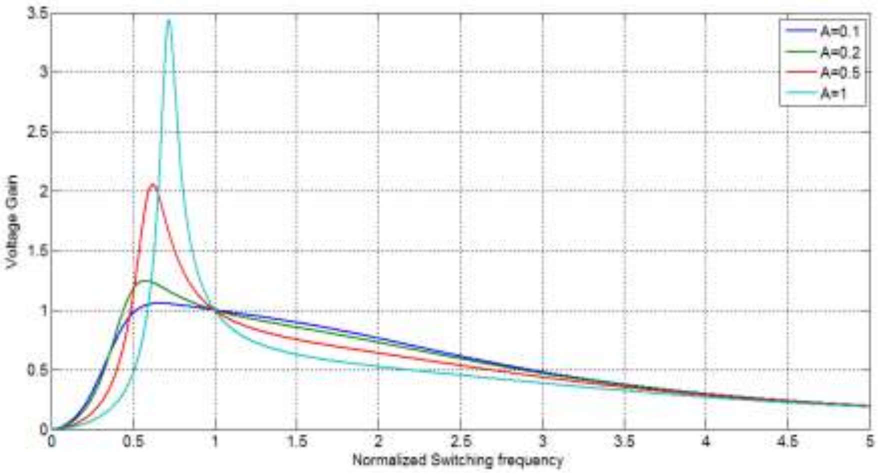


Figure 9. Frequency response of output voltage gain with different inductor ratios

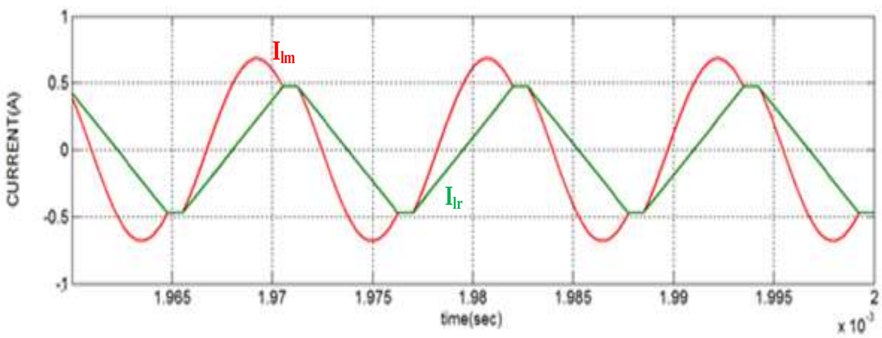


Figure 10. Output current at maximum power operating in region 2

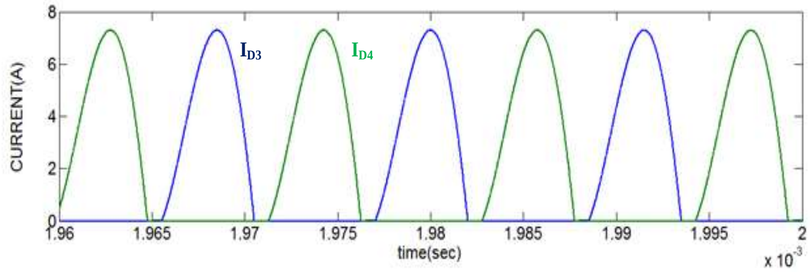


Figure 11. Output current at maximum power operating in region 2

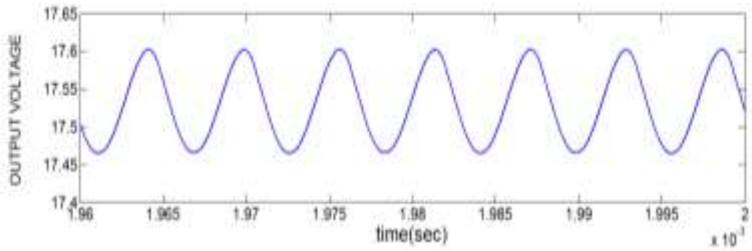


Figure 12. Output voltage at maximum power

Figure 13 shows I-V characteristics of I-V curve and their corresponding frequency is shown in Figure 14. It can be observed that points “E”, “F” and “G” are located in region 2 to obtain high efficiency in high output-power operations. It can be seen from above figure that in order to achieve full I-V characteristics frequency have to vary from 80 kHz to 175 kHz. But for half insolation as shown in Figure 13, in order to achieve open circuit voltage and short circuit frequency of LLC converter have to vary more. It is very difficult to build high variable frequency pulse generator and it will also increase gate driver circuit loss to a significant value. Therefore, efficiency of emulator will decrease.

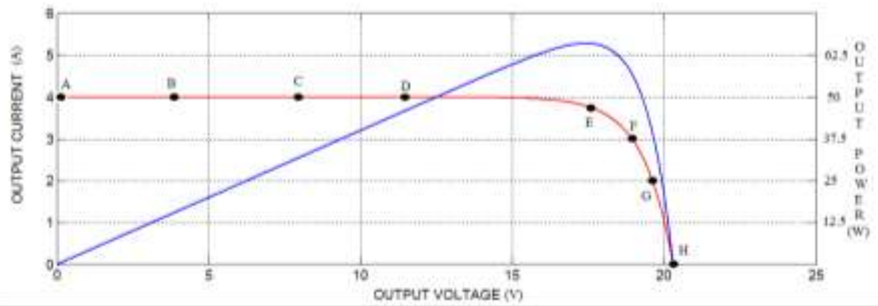


Figure 13. The V–I curve of the LLC resonant converter

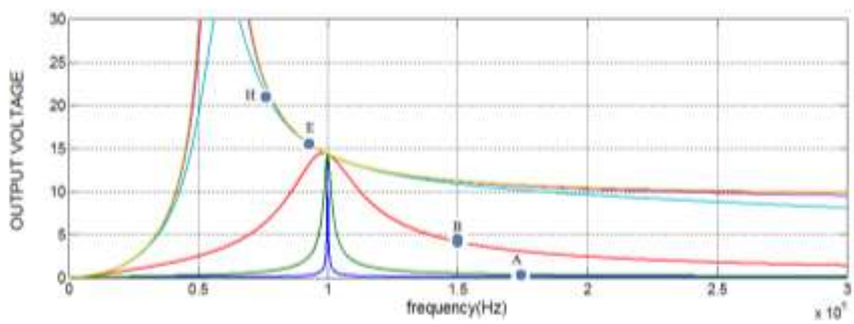


Figure 14. Frequency response of output voltage gain

Figure 15 and 16 shows output voltage and current of the quasi resonant buck converter respectively. Figure 17 shows resonant current at maximum power. Figure 18 and 19 shows switch voltage v/s duty cycle of quasi buck resonant converter. We can observe from Figure 18 that ZVS of switch is achieved and maximum switch voltage is six times of input voltage as designed. If we want to achieve zero voltage for current less than 0.8 amps, we have to increase maximum switch voltage. Suppose we want to achieve zero voltage for current up to 0.4 amps. Then switch voltage will be 11 times of input voltage as shown in Figure 19.

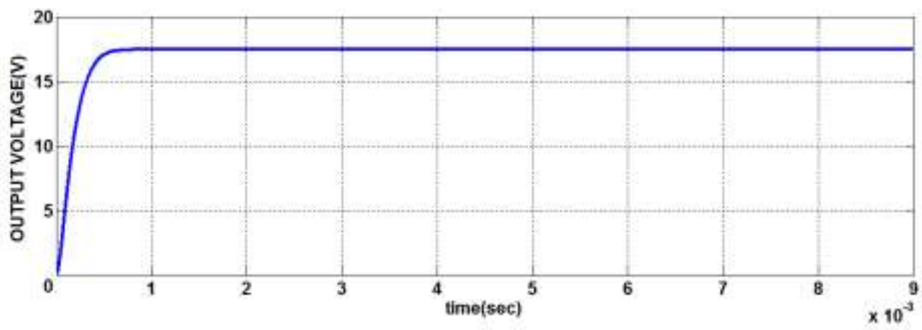


Figure 15. Output voltage of quasi resonant buck converter

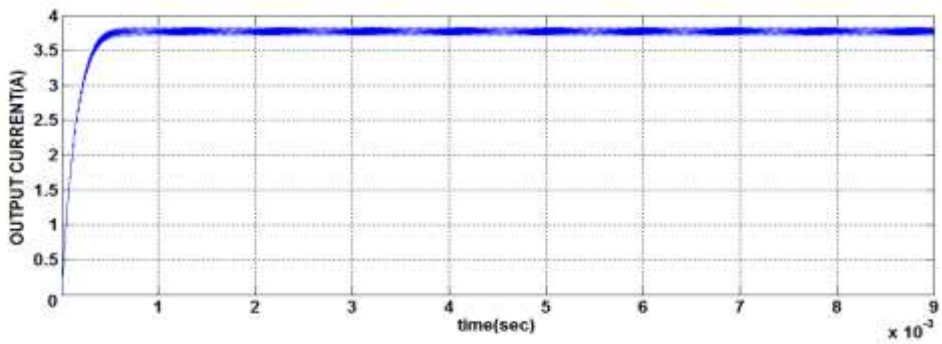


Figure 16. Output current of quasi resonant buck converter

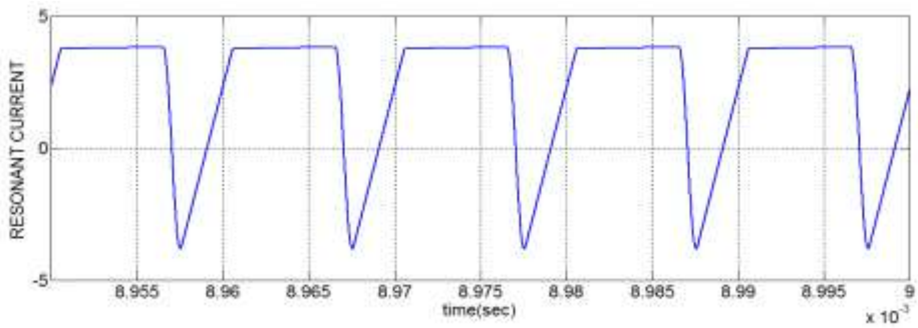


Figure 17. Resonant current at maximum power

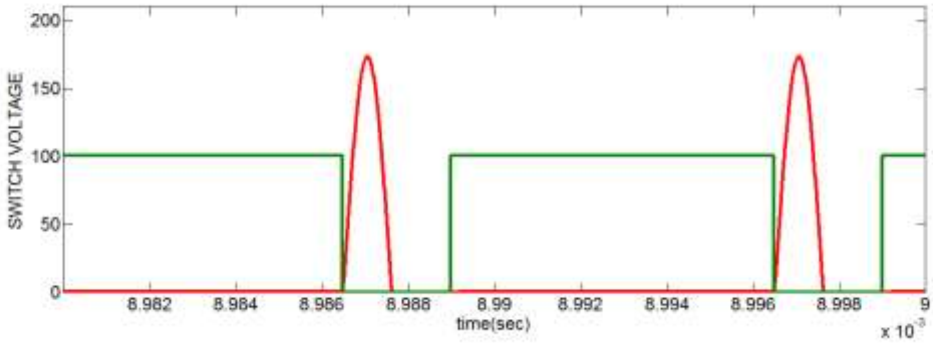


Figure 18. Switch voltage vs. duty cycle

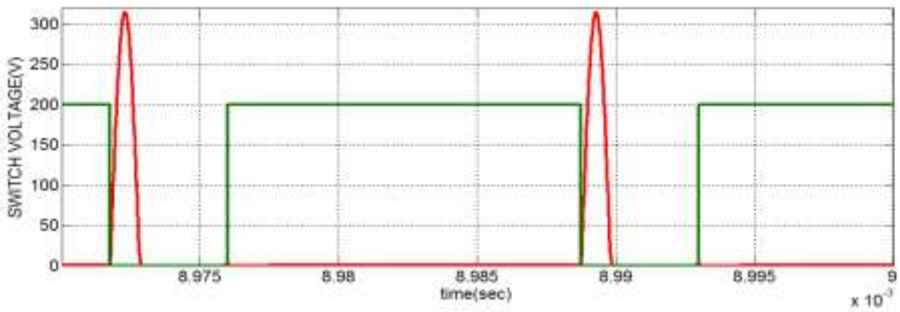


Figure 19. Switch voltage vs duty cycle

Table 4. Comparison of PWM based and resonant based DC-DC Converter

| Parameters | PWM based Buck | Resonant based LLC |
|---|---|---|
| No. of switches | 1 | 2 |
| No of diodes | 1 | 2 (half bridge) or 4 (full bridge) |
| No. of inductors | 1 | 2 |
| No. of capacitors | 1 | 2 |
| ZVS | Not available | Available |
| ZCS | Not available | Available |
| Isolation | Not available | Available |
| Voltage gain | Less than 2 | Can be up to 1 |
| Efficiency | Low | High |
| Cost | Low | High |
| Control complexity | Less | More |

## 6. CONCLUSION

We have developed and studied three type of convertor for photo voltaic emulator. Buck have advantage of simple control, low cost, can be easily modified to achieve I-V characteristics at different solar insolation. We found it is quite difficult for Z source converter to give full I-V characteristics as discussed in section 3. We have also studied different type of resonant converter to get full I-V characteristics. Resonant converter like LLC is very efficient for photo voltaic emulator if designed for particular solar insolation, but when this converter is used for variable solar insolation then the variation in switching frequency increase. It is impractical to build a gate driver circuit of wide frequency generator and also gate drive loss become significant while operating. Quasi buck also gives very good efficiency at maximum power point. But as discussed in section 4, in order to achieve full characteristics switch voltage have to increase. In order to achieve ZVS at open circuit condition, peak voltage will go to infinity. There is also problem at different solar insolation because for low value of solar insolation ZVS cannot be achieve on full I-V characteristics if short circuit current is less than $I_{Omin}$.

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