Comparative Analysis of LLC Resonant and Quasi Resonant Converter for Photo Voltaic Emulator

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Abstract— **The paper presents a comparative analysis of the two resonant based converter topologies. The converter topologies selected are LLC resonant converter and the Quasi resonant converter. The modeling, analysis and control of both the converter is done and presented here for the case of the photovoltaic (PV) emulator. 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 complete system is modelled in MATLAB® Simulink SimPowerSystem software package. The Simulation results obtained from the MATLAB® Simulink SimPowerSystem software package for both 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.**

Keywords—Buck Converter, LLC Resonant Converter, Quasi Resonant Buck Converter, Photo Voltaic Emulator, Simulink.

I. INTRODUCTION

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
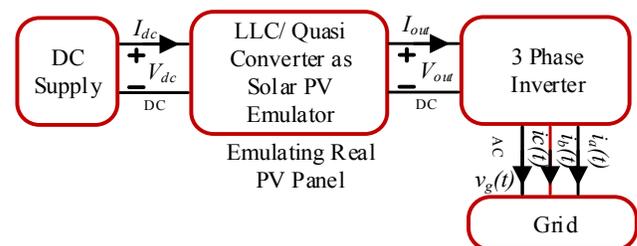

Fig. 1 PV emulator connection to a grid connected 3 phase inverter.

inverters or MPPT charge controllers as shown in Fig. 1. In Fig. 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 [9-11]. 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 [12]. The DC/DC converter when designed properly can precisely describe the voltage-current and voltage-power characteristics of PV cell/array [13].

Many authors have contributed to the small-signal modeling of LCC resonant topology. A small-signal model for LCC
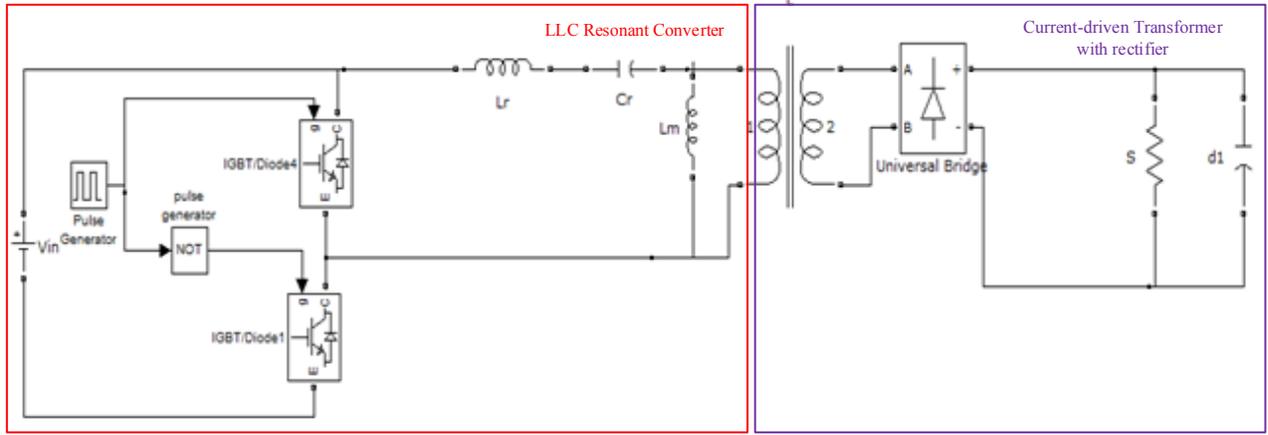
Fig. 2 Simulink block diagram of current mode control of LLC resonant converter

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

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 [14-15]. A new topology for Quasi-square-wave converters has been developed in 1988, and its detailed analysis and modeling is available in literature [16]. 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.

II. LLC RESONANT CONVERTER BASED PV EMULATOR

PV emulator can be implemented using LLC resonant converter (shown in Fig. 2). This 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).

Where,

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

$$R_i \cdot \omega_L \cdot C_r$$

$$\omega_L = 2\pi f_L = \frac{1}{\sqrt{L_r * C_r}}$$
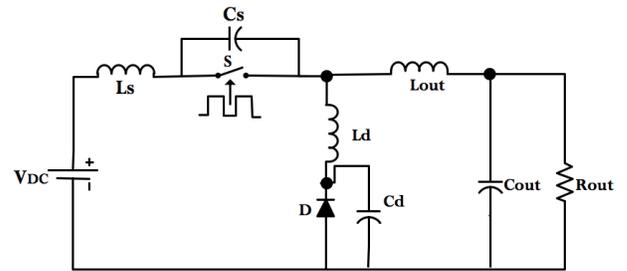
Fig. 3 Circuit Diagram of Quasi Resonant Buck Converter

III. 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 fig. 3. 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.

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.

$$V_{INmax} = V_{INmin} = V_{IN} = 30 \ volt \qquad (2)$$

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

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 ω_R = 8.45 nF

IV. SIMULATION RESULTS AND DISCUSSION

Simulation is done in MATLAB® Simulink environment. The parameters used for LLC resonant and quasi resonant buck converters are listed in table 1 and table 2 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 as 75 ohm, 23.8µH and 4.225 nF respectively. Fig. 4 and 5 shows the frequency response of output voltage gain with different Q factor and differnt inductor ratios respeectively. Fig. 6 shows resonant current and magnetizing current for maximum power, whereas Fig. 7 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. Fig. 8 shows output voltage at maximum power. Fig. 9 shows I-V characteristics of I-V curve and their corresponding frequency is shown in Fig. 10. 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 Fig. 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 Fig.9, 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.

Table 1. 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 2. 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 (I₀ₘᵢₙ)	0.4 A
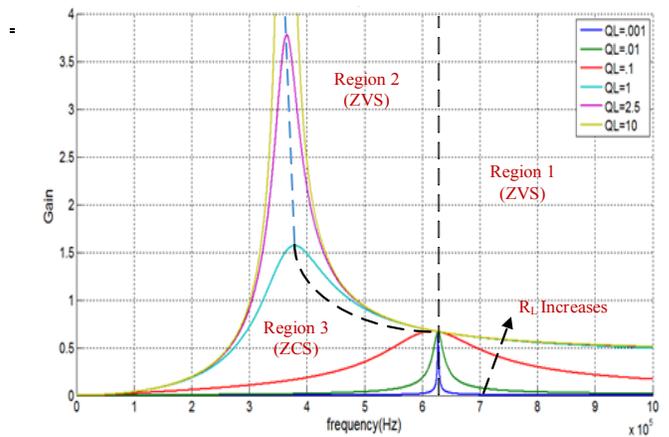
Fig. 4 Frequency response of output voltage gain of the LLC resonant converter
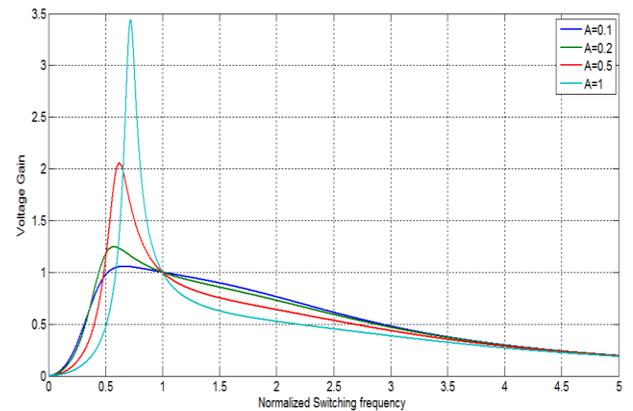
Fig. 5 Frequency response of output voltage gain with different inductor ratios

Fig. 11 shows resonant current at maximum power. Fig. 12 and 13 shows switch voltage v/s duty cycle of quasi buck
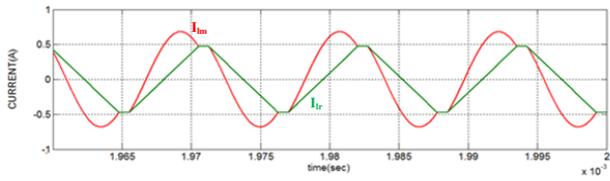
Fig. 6. Output Current at maximum power operating in region 2
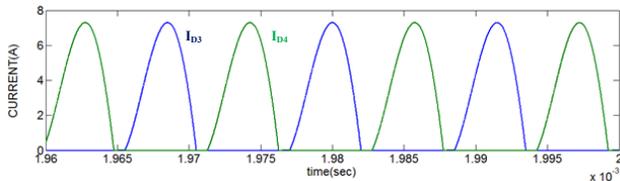
Fig. 7. Output Current at maximum power operating in region 2
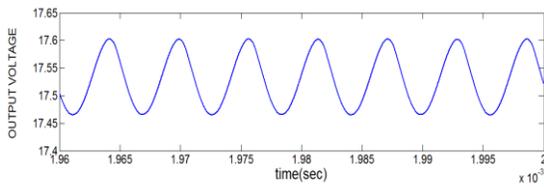
Fig. 8. Output voltage at maximum power
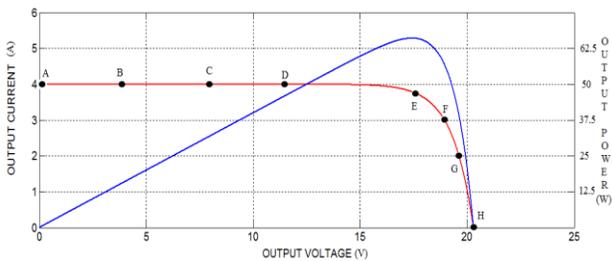
Fig. 9. The V–I curve of the LLC resonant converter
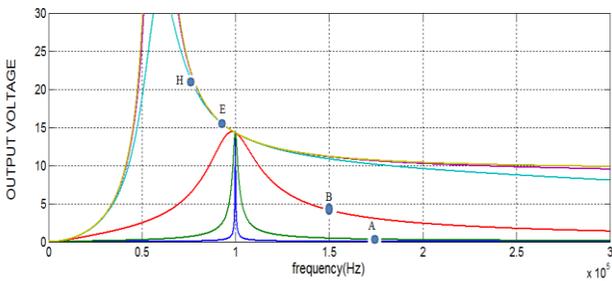
Fig. 10. Frequency response of output voltage gain

Fig. 11 Resonant Current at maximum power

Figure 12. Switch voltage vs. duty cycle

Fig. 13. Switch voltage vs. duty cycle

resonant converter. We can observe from Fig. 12 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 Fig. 13.
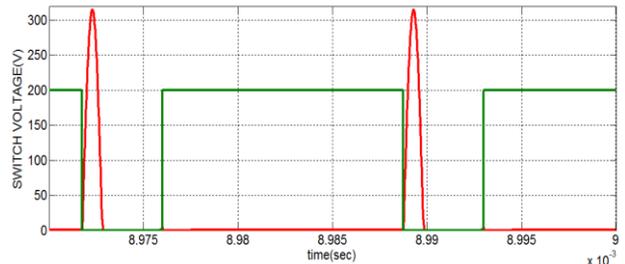
V.   CONCLUSIONS

Two types of DC-DC converter has been studied, analyzed and simulated in the simulation environment for photo voltaic emulator. 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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