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Closed-Loop High-Step up Converter with Soft Switching in PV Systems

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ABSTRACT:

In the last several years, with the tension of global fossil energy, the renewable energy power systems, which are mainly on the photovoltaic (PV) power systems, are developing rapidly. In a PV power system, the output voltages of the PV panels are usually low and vary widely under the influences of weather and environment. The unregulated low voltage of PV panels, which cannot be provided for inverters, must be boosted and regulated through the high-gain converters. In this paper, a new High Step up DC-DC Converter is introduced for application in PV systems. The provided topology includes a boost converter using coupled inductors to increase the voltage gain. The only switch on this Converter is switched under Zero- Current Switching (ZCS), and also, all the diodes are switched on and off less than Zero-Current Switching. The voltage stress on the switch and all the diodes is much lower than the output voltage, and this makes the efficiency of this converter higher. The simulation model and the results are analyzed using MATLAB/Simulink.

Keywords: Photovoltaic (PV), High Step up DC-DC Converter, Zero-Current Switching.

(1) Introduction

Energy generation, transmission and distribution are undergoing profound changes with the emergence of localized grids in favour of a centralized grid. Whatever the reason: disaster mitigation, energy independence or financial gain, they all subscribe to and advance the separation from a central grid. And, it is happening across all sectors, from residential to commercial, communities to nations and urban to rural. These localized grids – mini grids, Micro grids, nano grids and pico grids – however are not just miniaturizations of the grid as we know it. They are more in tune with today's energy and how it is used. And, not just the use, but also the generation, as diverse energy sources become more technologically available and affordable. According to the emerge Alliance, 80% of all AC electricity is now being used by DC based power electronics [1] heralding the change to energy sources that don't incur significant conversion losses at the point of use.

The general term of these localized grids, Microgrids [2], can be divided into AC and DC. However, the problems associated with AC Microgrids – synchronization of generators, reactive power and line unbalances, as well as their energy losses when converting to DC, favours the move to the DC microgrid. Such DC Microgrids may include AC and DC loads, dispatch able and non-dispatch able generators, energy storage, common distribution, management and demand response, and, a tether to the grid, where available, for increased reliability of service.

Renewable energy sources play an important role in electricity generation. The benefits of renewable energy system are more attractive than they ever had before. Specially, energy from the sun is the best option for electricity generation as it is available everywhere and is free to harness. The merits of solar PV system are cleanness, relative lack of noise or movement, as well as their ease of installation and integration when compared to others. Electricity from the sun can be generated through the solar photovoltaic modules (SPV). The SPV comes in various power output to meet the load [1]. However, the output power of a PV panel is largely determined by the solar irradiation and the temperature of the panel. At a certain weather condition, the output power of a PV panel depends on the terminal voltage of the system. To maximize the power output of the PV system, a high efficiency, low-cost DC/DC converter with a voltage and current feedback signal is employed to control the output voltage of the PV system at optimal values in various solar radiation conditions [2].

The DC/DC converters are non-linear dynamic systems. The primary reasons for the non-linearity are due to high frequency switching, power devices like Metal Oxide Semiconductor Field Effect Transistor (MOSFETs), diodes and passive components such as inductors and capacitors.

Therefore, there is a need for an optimal control technique for these DC/DC converters which can deal with their intrinsic non-linearity and variations in the load ensures stability in any operating condition while taking care of obtaining the fast transient response.

2 Topology of Proposed Converter

Fig.1 shows the power circuit of the proposed high gain Hybrid Series Inductor Capacitor (H-SLC). The proposed converter comprises of one high and one low side switch and two legs of switched inductor (SI) cells. Inductors L1, L2 and L3 along with diodes D1, D12, D2a, D2b, D23, and D3 form the first SI cell. The first cell is connected to the positive polarity of the DC supply through switch S1 and is operated by turning the switch S1 ON and OFF periodically. The second SI cell is an exact replica of the first; the second SI cell is connected to the negative terminal of the supply while S2 aids in charging and discharging the SI cell. Diode Do acts as output diode while capacitor Co serves as output capacitor. The voltage gain of this converter can be further extended by adding "n" number of SI in each cell. Fig.2 shows the circuit configuration of a generalised H-SLC with "n" switched inductor in each cell. In this paper, a 3-level H-SLC is explored in detail.

3 Operation Principle of Proposed Converter

In this section, the converter's operating principle is discussed under continuous conduction mode (CCM). The working of the converter is understood using Modes 1 and 2. The complete operating principle is detailed using the valid assumption that all devices and passive components are ideal.

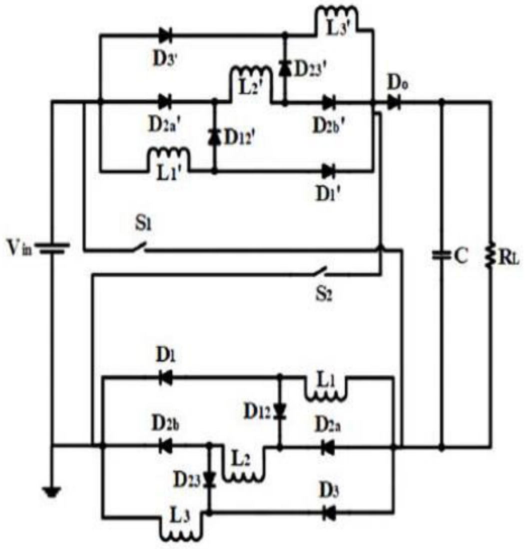

Fig. 1. Power circuit diagram of the proposed converter

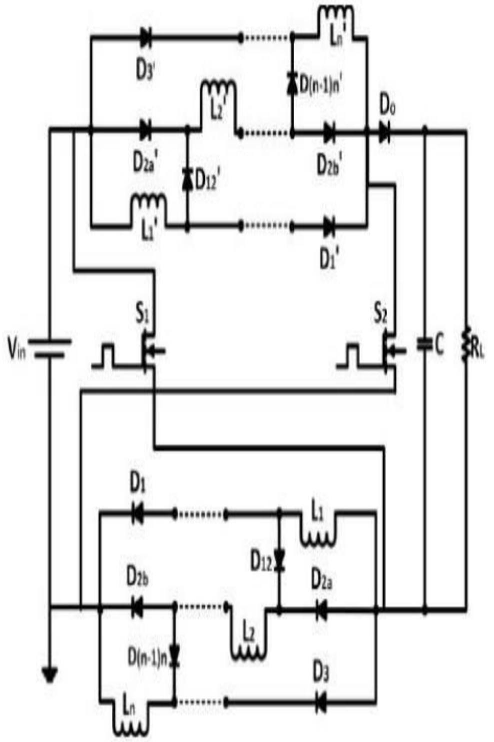

Fig.2. Power circuit diagram of the generalised proposed converter family

Mode 1[t0-t1]: Mode 1 commences at time t=to. Both the switches S1 and S2 are turned ON simultaneously. Inductors of the upper cell L1, L2, L3 begin to store energy and charge towards the input voltage through S2 while the inductors L1', L2', L3' charge through the switch S1. As the inductors continue to store energy, diodes D12, D23, D12', D23' and Do are reverse biased. The output capacitor Co discharges and meets the load requirement. Mode 1 comes to an end when the inductor current reaches its maximum value and the switches S1 and S2 are turned OFF at t=t1. Fig.3 shows the equivalent circuit during Mode 1. The equation during Mode 1 is given by (1).

$$i_{L1}(t)=i_{L2}(t)=i_{L3}(t)=i_{L1}'(t)=i_{L2}'(t)=i_{L3}'(t)=\frac{V_{in}}{L} \tag{1}$$

Mode 2[t1-t2]: In Mode 2, S1 and S2 are simultaneously turned OFF and the six inductors transfer energy to the output in series. During this mode, diodes D12, D23, D12' and D23' are forward biased, while the rest of the diodes become reverse biased and do not conduct. Fig.4 shows the equivalent circuit for this mode. The equation governing Mode 2 is given by (2).

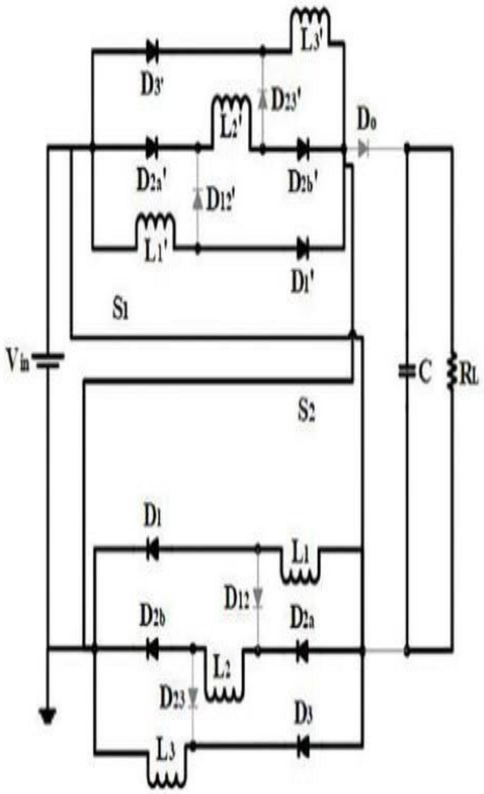

Fig. 3. Equivalent circuit during Mode 1

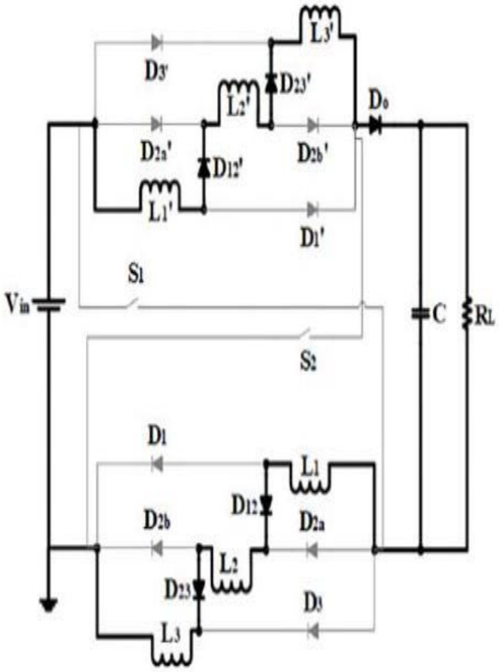

Fig. 4. Equivalent circuit during Mode 2

$$i_{L1}(t)=i_{L2}(t)=i_{L3}(t)=i_{L1}'(t)=i_{L2}'(t)=i_{L3}'(t)=\frac{V_{in}-V_o(t)}{L}t \tag{2}$$

4. Analysis under Steady-State Conditions

In this section, expressions for voltage gain and design details of switches and diodes are derived.

4.1 Analysis under Steady-State condition

The steady state voltage induced across inductors in Mode 1 is given as

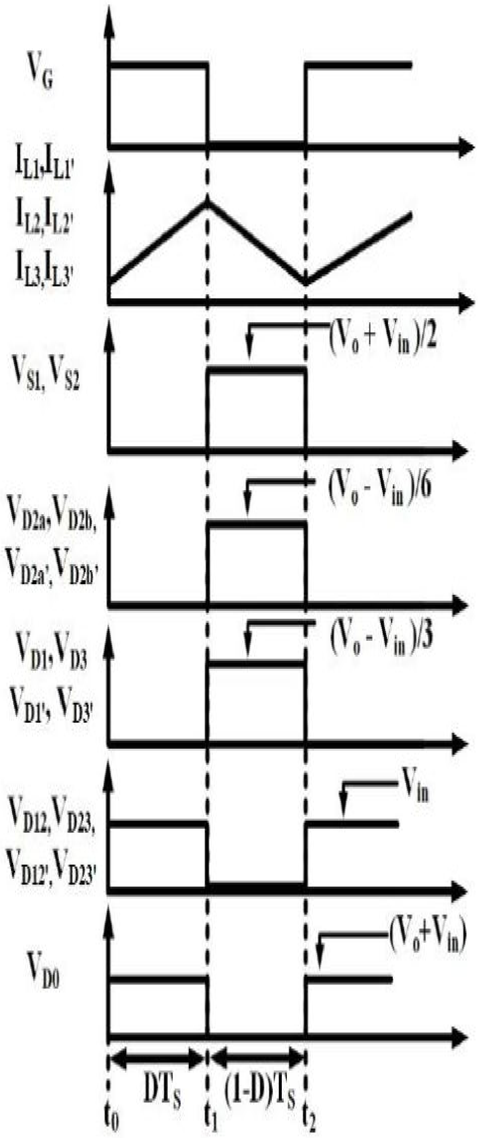

Fig. 5. Characteristic waveforms of the proposed converter

$$V_{L1}=V_{L2}=V_{L3}=V_{L1'}=V_{L2'}=V_{L3'}=V_{in} \quad (3)$$

During Mode 2, the voltage induced in the inductors is given by

$$V_{L1}=V_{L2}=V_{L3}=V_{L1'}=V_{L2'}=V_{L3'}=\frac{V_{in}-V_o}{6} \quad (4)$$

Using volt-second balance concept, expression for voltage gain is deduced as

$$G_{CCM}=\frac{V_o}{V_{in}}=\frac{1+5D}{1-D} \quad (5)$$

For a generalized structure, voltage gain expression is

$$G_{CCM}=\frac{V_o}{V_{in}}=\frac{1+(2n-1)D}{1-D} \quad (6)$$

At D=0.6, the converter yields an ideal voltage gain of 10 which is sufficient enough to connect the load to a 380V DC bus from a 35-40V input.

4.2 Voltage Stress

The voltage stress across D1, D1’, D3, D3’ is given by

$$V_{D1}=V_{D1}'=V_{D3}=V_{D3}'=\frac{V_o-V_{in}}{3} \quad (7)$$

Voltage stress across D2a, D2a’, D2b, D2b’ is given by

$$V_{D2a}=V_{D2a}'=V_{D2b}=V_{D2b}'=\frac{V_o-V_{in}}{6} \quad (8)$$

Similarly, the voltage stress across D12, D12’, D23, D23’ is given by

$$V_{D12}=V_{D12}'=V_{D23}=V_{D23}'=V_{in} \quad (9)$$

The voltage stress across D0 is expressed as

$$V_{D0}=V_o+V_{in} \quad (10)$$

The voltage across the power switches is expressed as

$$V_{S1}=V_{S2}=\frac{V_o-V_i}{6} \quad (11)$$

4.3 Current Stress

The current stress on the inductors is given by

$$\frac{I_L}{I_O}=\frac{G+5}{6} \quad (12)$$

4.4 Design of Passive Components

The critical values need to be set while keeping in mind the minimum current ripple for the protection of the system. In the given converter, the critical value of inductor is given

$$L_{cri}=\frac{D(1-D)R_L}{2f(1+5D)}=\frac{DR_L}{2fG} \quad (13)$$

Where D is Duty Ratio, RL is load resistance, G is voltage gain and f stands for switching frequency. Output capacitor value is estimated using duty ratio D, voltage gain G and the switching frequency f as

$$C_{cri}=\frac{D}{2fG} \quad (14)$$

5. Closed Loop Control System

A control system is a system of devices or set of devices, that manages commands, directs or regulates the behaviour of other device(s) or system(s) to achieve desire results. In other words the definition of control system can be rewritten as A control system is a system, which controls other system. As the human civilization is being modernized day by day the demand of automation is increasing accordingly. Automation highly requires control of devices. In recent years, control systems plays main role in the development and advancement of modern technology and civilization. Practically every aspects of our day-to-day life is affected less or more by some control system. A bathroom toilet tank, a refrigerator, an air conditioner, a geezer, an automatic iron, an automobile all are control system. These systems are also used in industrial process for more output. We find control system in quality control of products, weapons system, transportation systems, power system, space technology, robotics and many more. The principles of control theory is applicable to engineering and nonengineering field both.

5.1 Feature of Control System

The main feature of control system is, there should be a clear mathematical relation between input and output of the system. When the relation between input and output of the system can be represented by a linear proportionality, the system is called linear control system. Again when the relation between input and output cannot be represented by single linear proportionality, rather the input and output are related by some non-linear relation, the systemis referred as non-linear control system.

5.2 Requirement of Good Control System

- **Accuracy:** Accuracy is the measurement tolerance of the instrument and defines the limits of the errors made when the instrument is used in normal operating conditions. Accuracy can be improved by using feedback elements. To increase accuracy of any control system error detector should be present in control system.
- **Sensitivity:** The parameters of control system are always changing with change in surrounding conditions, internal disturbance or any other parameters. This change can be expressed in terms of sensitivity. Any control system should be insensitive to such parameters but sensitive to input signals only.
- **Noise:** An undesired input signal is known as noise. A good control system should be able to reduce the noise effect for better performance.
- **Stability:** It is an important characteristic of control system. For the bounded input signal, the output must be bounded and if input is zero then output must be zero then such a control system is said to be stable system.
- **Bandwidth:** An operating frequency range decides the bandwidth of control system. Bandwidth should be large as possible for frequency response of good control system.
- **Speed:** It is the time taken by control system to achieve its stable output. A good control system possesses high speed. The transient period for such system is very small.
- **Oscillation:** A small numbers of oscillation or constant oscillation of output tend to systemto be stable.

5.3 Closed Loop Control System

Control system in which the output has an effect on the input quantity in such a manner that the input quantity will adjust itself based on the output generated is called **closed loop control system**. Open loop control system can be converted in to closed loop control system by providing a feedback. This feedback automatically makes the suitable changes in the output due to external disturbance. In this way closed loop control system is called automatic control system. Figure 6 below shows the block diagram of closed loop control system in which feedback is taken from output and fed in to input.

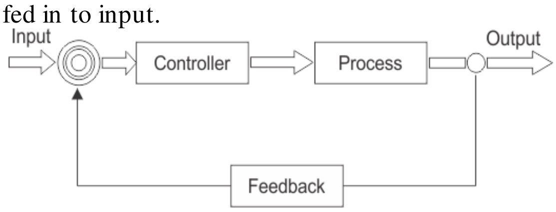

Fig 6 block diagram of closed loop control system

Advantages of Closed Loop Control System

1. Closed loop control systems are more accurate even in the presence of non-linearity.
2. Highly accurate as any error arising is corrected due to presence of feedback signal.
3. Bandwidth range is large.
4. Facilitates automation.
5. The sensitivity of systemmay be made small to make system more stable.
6. This systemis less affected by noise.

Disadvantages of Closed Loop Control System

1. They are costlier.
2. They are complicated to design.
3. Required more maintenance.
4. Feedback leads to oscillatory response.
5. Overall gain is reduced due to presence of feedback.
6. Stability is the major problem and more care is needed to design a stable closed loop system.

(6) SIMULATION RESULTS:

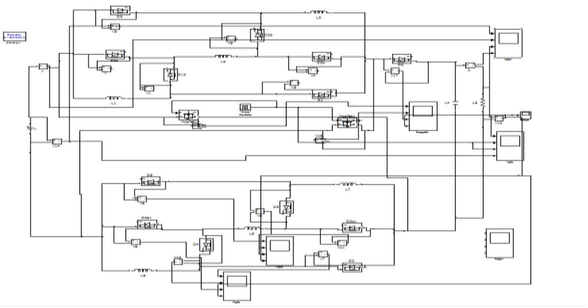

Fig 7 Simulink Diagram of Proposed DC_DC Converter

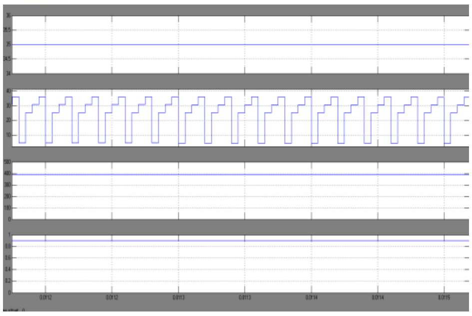

Fig 8 switches voltage gain capability

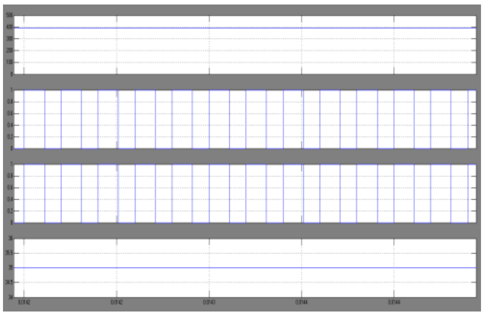

Fig 9 switches capability

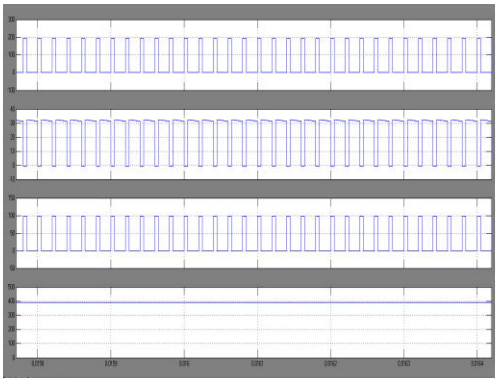

Fig 10 voltage stress on diodes and operating efficiency

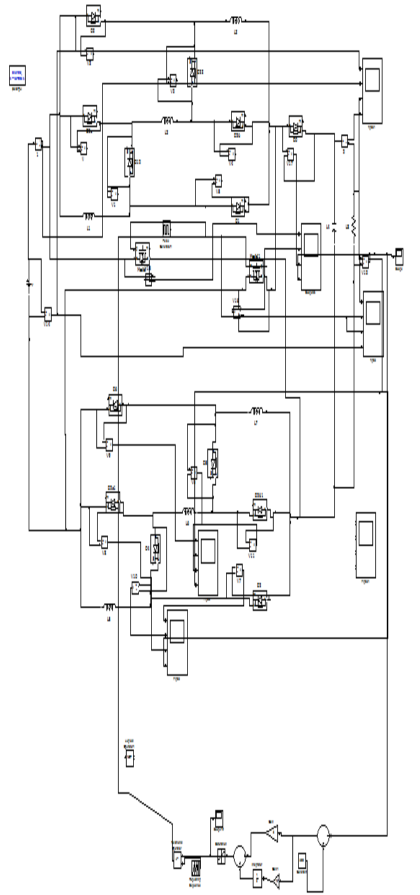

Fig 11 Simulink Diagram Of Proposed DC_DC Converter with closed loop controller

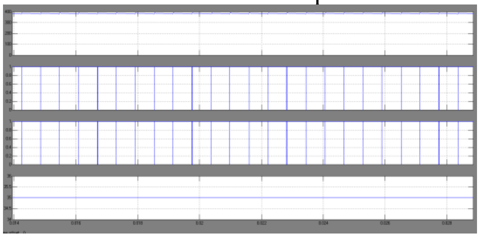

Fig 12 switches voltage gain capability in closed loop controller

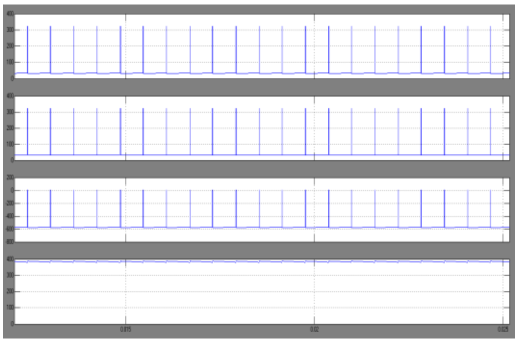

Fig 13 switches wave form in closed loop controller

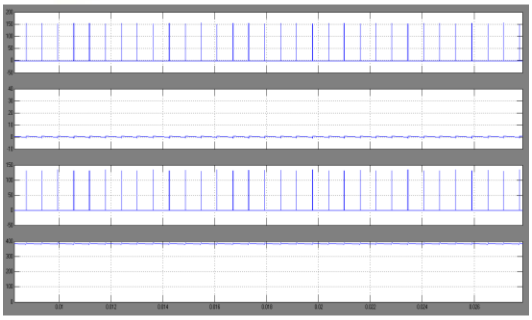

Fig 14 diodes in SL cells in closed loop controller

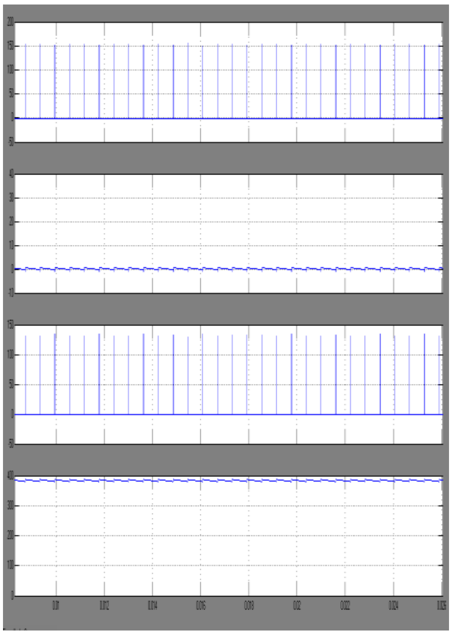

Fig.15. Simulation waveforms demonstrating voltage stress on diodes and operating efficiency

(7) CONCLUSION

This paper presents a high gain DC-DC converter with closed loop based on modular switched-inductor network. Each SI cell in the proposed converter with closed loop used 3 inductors which stored energy in parallel and discharged in series. Resultantly, the converter with closed loop yielded a voltage gain of 10.8 at a maximum efficiency of 94.45% at full load power rating of 210W. Since a hybrid voltage gain extension mechanism was employed, the switches were subjected to a lower voltage stress of 55% of output voltage. Due to the switched-inductor cells, the current stress on the individual inductors was reduced. Consequently, the stray loss due to the inductors was less and resulted in good operating efficiency. The modularity of the proposed with closed loop gain extension technique is another advantageous feature of the proposed converter with closed loop. Considering the high voltage gain ability, reduced voltage stress on the switches and the facility to scale up, this proposed converter is more preferred for PV fed application.

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