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High Voltage Gain DC-DC Converter with Reduced Components Voltage Stress for Photovoltaic

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ABSTRACT

In this paper a novel high step up single switch dc dc converter with high efficiency is proposed. In this converter, high voltage gain is achieved using coupled inductor and diode capacitor techniques. Hence, there is no need to use extreme duty cycle. Moreover, the output diode reverse recovery problem has been alleviated in the proposed converter. The voltage stress across all circuit elements has been reduced which decreases the overall size and cost of the proposed converter. Operation principles and steady state analysis of the proposed topology are discussed in detail. Finally, some simulations have done to verify mathematical derivations and mentioned features of the proposed converter.

Keywords*-high voltage gain, reduced switch stress, dc-dc, reverse recovery.*

I. INTRODUCTION

Fuel cell has a slow dynamic response, so the power supply from the fuel cell cannot cope with the power demand during a transient load. Thus, a secondary power source is required to compensate the power difference between the fuel cell and the load, and a battery is generally used to supply a transient power. The power flow between the fuel cell and the battery is managed by a bidirectional dc/dc converter. Conventional isolated/bidirectional dc/dc converters for high-power applications have a voltage-fed full-bridge (FB) (VF-FB) scheme in the high-voltage (HV) side and various current-fed (CF) schemes in the low-voltage (LV) side in general because voltage-fed half-bridge (HB) and voltage-fed push–pull (PP) schemes have disadvantages of high current stress and/or high voltage stress. According to which schemes are used in the LV side, they have several variations such as VF-FB + two-inductor CF-HB, VF-FB + CF-FB, and VF-FB + CF-PP with six or eight switches. These converters suffer from efficiency decrease at a light-load condition and low efficiency at boost-mode operation due to switching loss. Also, they require a snubber circuit such as an active-clamp circuit to alleviate turn-off voltage spikes in the LV side, which increases the switch number by one or two as a result.

In this letter, a two-stage isolated/bidirectional dc/dc converter adopting a current ripple reduction technique is proposed. The resonant converter with two bridges takes in charge of electrical isolation and constant gain, and the bidirectional control is accomplished using only the second stage with a single bridge. To reduce rms currents in the HV source and link capacitor, capacitor division and synchronizing operation of two stages are adopted.

II. Brief Review of Control Techniques for DC-DC converters

DC-DC converters are one of the important electronic circuits, which are widely used in power electronics . The main problem with operation of DC-DC converter is unregulated power supply, which leads to improper function of DC -DC converters. There are various analogue and digital control methods used for dc-dc converters and some have been adopted by industry including voltage- and current-mode control techniques. The DC-DC converter inputs are generally unregulated dc voltage input and the required outputs should be a constant or fixed voltage. Application of a voltage regulator is that it should maintains a constant or fixed output voltage irrespective of variation in load current or input voltage. Various kinds of voltage regulators with a variety of control schemes are used to enhance the efficiency of DC-DC converters.

Today due to the advancement in power electronics and improved technology a more severe requirement for accurate and reliable regulation is desired . This has led to need for more advanced and reliable design of controller for dc-dc converters. There are various types of DC-DC converters required for particular purpose like Buck, Boost, Buck and Boost, Cuk and flyback. These all DC-DC converters have their specific configurations to complete their tasks. Varieties in DC-DC converter required different type of controlling techniques because single technique cannot be applied to all converters as the all have different specifications.

The principal aim of this chapter is to provide an overview of all the control techniques used to facilitate the performance of various kinds of DC-DC converters. In this chapter the basic concept, advantages and disadvantage of each control technique are presented in brief.

Fuzzy logic controller

The nature of Fuzzy control is non-linear and adaptive and it is a practical alternative for a variety control applications . The concept of Fuzzy Logic (FL) was conceived by LotfiZadeh, a professor at the University of California at Berkley. According to him, it not as a control methodology, but as a way of processing data by allowing partial set membership function rather than crisp (Fig.2.5). There are four main elements in the fuzzy logic controller system structure named as: Fuzzifier, Rule base, Inference engine and defuzzyfier. The working of fuzzy logic controller structure can be easily understood from the block diagram (Fig.2.5). Its working is divided in 3 main steps: i. Fuzzification. ii. Inference. iii. Defuzzification.

In this process, at the first step crisp set used as input data or non-fuzzy data, after this it is converted to a fuzzy set using fuzzier by the help of linguistic variables, fuzzy linguistic terms and membership functions.

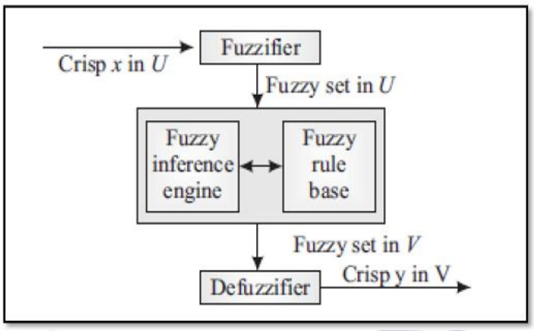


Fig 2.5: Overview of fuzzy logic controller process

The most important thing regarding fuzzy logic is that a numerical value does not have to be fuzzified using only one membership function. Membership functions vary such as Triangular, Gaussian, Trapezoidal, Generalized Bell and Sigmoidal. Rule base is the backbone of fuzzy logic controllers.

Rule Base: i. The purpose of rule base is to control the output variable. ii. A fuzzy rule is a simple IF-THEN rule with a specific condition and conclusion, represented by the matrix table. iii. error and change in error are the two variables taken along the axes, and the conclusions are within the table.

Advantages of Fuzzy Logic Controller: i. Low-cost implementations based on cheap sensors, low-resolution analog-to-digital converter. ii. This systems can be easily upgraded by adding new rules to improve performance or add new features, iii. Fuzzy control can be used for the improvement of traditional controller systems. iv. It provides a robust performance under parameter variation and load disturbances. v. It has wider range of operating conditions than PID. vi. Can be operated with noise and disturbance of different natures. vii. Developing the fuzzy controller is much cheaper than developing a model based or other controllers for the same work.

The PWM frequency is important

The PWM is a large amplitude digital signal that swings from one voltage extreme to the other. And, this wide voltage swing takes a lot of filtering to smooth out. When the PWM frequency is close to the frequency of the waveform that you are generating, then any PWM filter will also smooth out your generated waveform and drastically reduce its amplitude. So, a good rule of thumb is to keep the PWM frequency much higher than the frequency of any waveform you generate.

Finally, filtering pulses is not just about the pulse frequency but about the duty cycle and how much energy is in the pulse. The same filter will do better on a low or high duty cycle pulse compared to a 50% duty cycle pulse. Because the wider pulse has more time to integrate to a stable filter voltage and the smaller pulse has less time to disturb it the inspiration was a request to control the speed of a large positive displacement fuel pump. The pump was sized to allow full power of a boosted engine in excess of 600 Hp.

III. PWM Controller Features

At idle or highway cruise, this same engine needs far less fuel yet the pump still normally supplies the same amount of fuel. As a result the fuel gets recycled back to the fuel tank, unnecessarily heating the fuel. This PWM controller circuit is intended to run the pump at a low speed setting during low power and allow full pump speed when needed at high engine power levels.

This controller offers a basic “Hi Speed” and “Low Speed” setting and has the option to use a “Progressive” increase between Low and Hi speed. Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor. Normally the controller keeps the motor at this Lo Speed except when Progressive is used and when Hi Speed is commanded (see below). Low Speed can vary anywhere from 0% PWM to 100%.

Progressive control is commanded by a 0-5 volt input signal. This starts to increase PWM% from the low speed setting as the 0-5 volt signal climbs. This signal can be generated from a throttle position sensor, a Mass Air Flow sensor, a Manifold Absolute Pressure sensor or any other way the user wants to create a 0-5 volt signal. This function could be set to increase fuel pump power as turbo boost starts to climb (MAP sensor). Or, if controlling a water injection pump, Low Speed could be set at zero PWM% and as the TPS signal climbs it could increase PWM%, effectively increasing water flow to the engine as engine load increases. This controller could even be used as a secondary injector driver (several injectors could be driven in a batch mode, hi impedance only), with Progressive control (0-100%) you could control their output for fuel or water with the 0-5 volt signal.

Progressive control adds enormous flexibility to the use of this controller. Hi Speed is that same as hard wiring the motor to a steady 12 volt DC source. The controller is providing 100% PWM, steady 12 volt DC power. Hi Speed is selected three different ways on this controller: 1) Hi Speed is automatically selected for about one second when power goes on. This gives the motor full torque at the start. If needed this time can be increased (the value of C1 would need to be increased). 2) High Speed can also be selected by applying 12 volts to the High Speed signal wire. This gives Hi Speed regardless of the Progressive signal.

When the Progressive signal gets to approximately 4.5 volts, the circuit achieves 100% PWM – Hi Speed.

IV. DC – DC Converters

Modern electronic systems require high quality, small,light weight, reliable, and efficient power supplies. Linear power regulators, whose principle of operation is based ona voltage or current divider, are inefficient. They are limited to output voltages smaller than the input voltage. Also,their power density is low because they require low-frequency(50 or 60Hz) line transformers and filters. Linear regulators can, however, provide a very high quality output voltage.

Their main area of application is at low power levels as lowdrop-out voltage (LDO) regulators. Electronic devices in linear regulators operate in their active (linear) modes. At higherpower levels, switching regulators are used. Switching regulators use power electronic semiconductor switches in on andoff states. Since there is a small power loss in those states (lowvoltage across a switch in the on state, zero current througha switch in the off state), switching regulators can achievehigh energy conversion efficiencies. Modern power electronicswitches can operate at high frequencies. The higher the operating frequency, the smaller and lighter the transformers, filterinductors, and capacitors. In addition, dynamic characteristicsof converters improve with increasing operating frequencies. The bandwidth of a control loop is usually determined by thecorner frequency of the output filter. Therefore, high operatingfrequencies allow for achieving a faster dynamic response torapid changes in the load current and/or the input voltage.High-frequency electronic power processors are used in dc–dc power conversion. The functions of dc–dc converters are:

- To convert a dc input voltage VS into a dc output voltage VO;
- To regulate the dc output voltage against load and line variations;
- To reduce the ac voltage ripple on the dc output voltage below the required level;
- To provide isolation between the input source and the load (isolation is not always required);
- To protect the supplied system and the input source from electromagnetic interference (EMI);
- To satisfy various international and national safety standards.

The dc–dc converters can be divided into two main types:hard-switching pulse width modulated (PWM) converters and resonant and soft-switching converters. This chapter dealswith the former type of dc–dc converters. The PWM converters have been very popular for the last three decades. They arewidely used at all power levels. Topologies and properties of PWM converters are well understood and described in literature. Advantages of PWM converters include low component count, high efficiency, constant frequency operation, relatively simple control and commercial availability of integrated circuit controllers, and ability to achieve high conversion ratios for both step-down and step-up application. A disadvantage of PWM dc–dc converters is that PWM rectangular voltage and current waveforms cause turn-on and turn-off losses in semiconductor devices which limit practical operating frequencies to a megahertz range. Rectangular waveforms also inherently generate EMI.

This chapter starts from a section on dc choppers which are used primarily in dc drives. The output voltage of dc choppers is controlled by adjusting the on time of a switch which in turn adjusts the width of a voltage pulse at the output. This is so called pulse-width modulation (PWM) control. The dc choppers with additional filtering components form PWM dc–dc converters.

Step-Down (Buck) Converter

The step-down dc–dc converter, commonly known as a buck converter, is shown in Fig. 4.4a. It consists of dc input voltage source VS, controlled switch S, diode D, filter inductor L, filter capacitor C, and load resistance R. Typical wave form sin the converter are shown in Fig. 4.4b under assumption that the inductor current is always positive. The state of the converter in which the inductor current is never zero for any period of time is called the continuous conduction mode (CCM). It can be seen from the circuit that when the switch Sis commanded to the on state, the diode D is reverse biased. When the switch S is off, the diode conducts to support an uninterrupted current in the inductor. The relationship among the input voltage, output voltage, and the switch duty ratio D can be derived, for instance, from the inductor voltage vL waveform (see Fig. 13.4b).According to Faraday's law, the inductor volt–second productover a period of steady-state operation is zero. For the buck converter

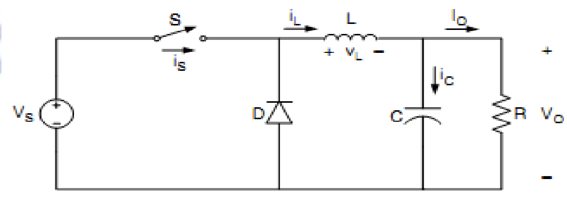
$$(V_S - V_O)DT = -V_O(1-D)T$$

Hence, the dc voltage transfer function, defined as the ratio ofthe output voltage to the input voltage, is

$$M_V \equiv \frac{V_O}{V_S} = D$$

It can be seen from above Eq.that the output voltage is always smaller than the input voltage.

The dc–dc converters can operate in two distinct modeswith respect to the inductor current iL. Figure 4.4b depictsthe CCM in which the inductor current is always greater thanzero. When the average value of the input current is low(high R) and/or the switching frequency f is low, the converter may enter the discontinuous conduction mode (DCM).In the DCM, the inductor current is zero during a portionof the switching period.



(a)

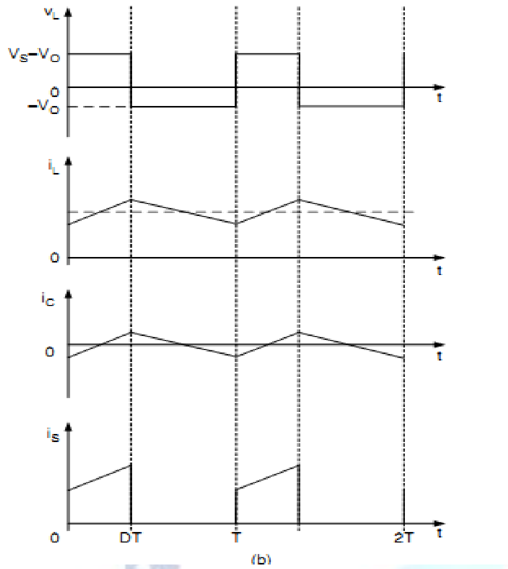


Fig 4.4: Buck converter: (a) circuit diagram and (b) waveforms.

The CCM is preferred for high efficiency and good utilization of semiconductor switches andpassive components. The DCM may be used in applicationswith special control requirements, since the dynamic order ofthe converter is reduced (the energy stored in the inductor iszero at the beginning and at the end of each switching period).It is uncommon to mix these two operating modes because ofdifferent control algorithms. For the buck converter, the valueof the filter inductance that determines the boundary betweenCCM and DCM is given by

$$L_b = \frac{(1-D)R}{2f}$$

Step-Up (Boost) Converter

5a depicts a step-up or a PWM boost converter. It iscomprised of dc input voltage source VS , boost inductor L,controlled switch S, diode D, filter capacitor C, and load resistance R. The converter waveforms in the CCMare presented inFig. 3.5b. When the switch S is in the on state, the current inthe boost inductor increases linearly. The diode D is off at thetime. When the switch S is turned off, the energy stored in theinductor is released through the diode to the input RC circuit.Using the Faraday's law for the boost inductor

$$V_S DT = (V_O - V_S)(1-D)T$$

From which the dc voltage transfer function turns out to be

$$M_V = \frac{V_O}{V_S} = \frac{1}{1-D}$$

As the name of the converter suggests, the output voltage is always greater than the input voltage. The boost converter operates in the CCM for L >Lb where

$$L_b = \frac{(1-D)^2 DR}{2f}$$

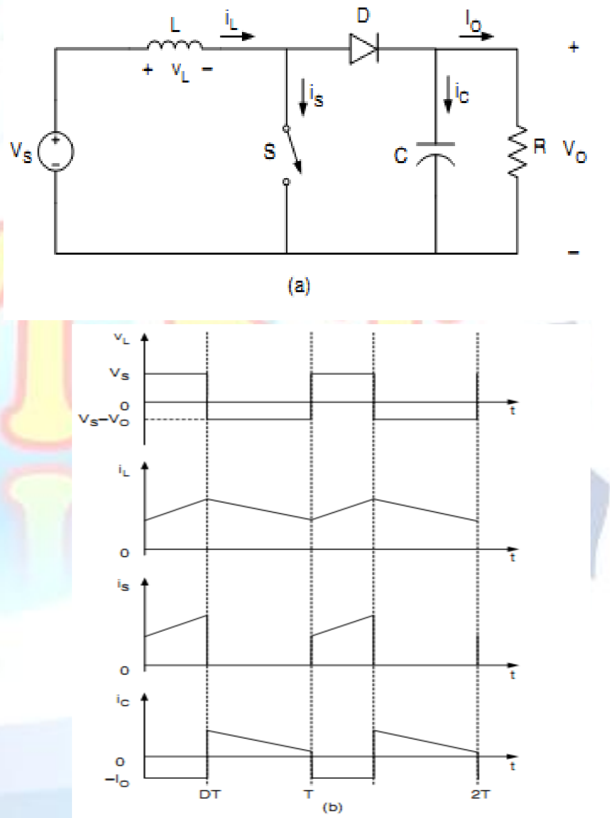


Fig 4.5: Boost converter: (a) circuit diagram and (b) waveforms

V. Operation of High Step-Up DC–DC Converter

The circuit topology of the proposed converter,which is composed of dc input voltage Vin, main switch S, coupled inductors Np and Ns, one clamp diode D1, clamp capacitor C1, two capacitors C2 and C3, two diodesD2 andD3, outputdiodeDo, and output capacitor Co. The equivalent circuit modelof the coupled inductor includes magnetizing inductor Lm,leakage inductor Lk and an ideal transformer. The leakage-inductor energy of the coupled inductor is recycled to capacitorC1, and thus, the voltage across the switch S can be clamped.

The voltage stress on the switch is reduced significantly. Thus,low conducting resistance RDS(ON) of the switch can be used.The original voltage-clamp circuit was first proposed in to recycle the energy stored in the leakage inductor. Basedon the topology, the proposed converter combines the conceptof switched-capacitor and coupled-inductor techniques. The Switched-capacitor technique in has proposed that capacitors can be parallel charged and series discharged to achieve ahigh step-up gain. Based on the concept, the proposed converterputs capacitors C2 and C3 on the secondary side of the coupledinductor. Thus, capacitors C2 and C3 are charged in parallel andare discharged in series by the secondary side of the coupledinductor when the switch is turned off and turned on. Becausethe voltage across the capacitors can be adjusted by the turnratio, the high step-up gain can be achieved significantly. Also,the voltage stress of the switch can be reduced. Compared to earlier studies, the parallel-charged current is notinrush. Thus, the proposed converter has low conduction loss.Moreover, the secondary-side leakage inductor of the coupledinductor can alleviate the reverse-recovery problem of diodes, and the loss can be reduced. In addition, the proposed converteradds capacitors C2 and C3 to achieve a high step-up gainwithout an additional winding stage of the coupled inductor.The coil is less than that of other coupled inductor converters.

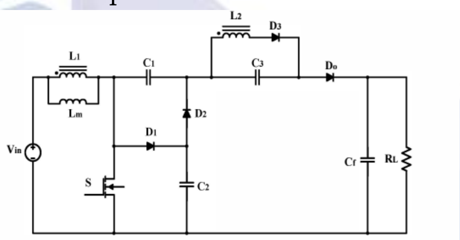


Fig 5.1 high step up dc –dc converter

The main operating principle is that, when the switch isturned on, the coupled-inductor-induced voltage on the secondary side and magnetic inductor Lm is charged by Vin.The induced voltage makes Vin, VC1, VC2, and VC3 releaseenergy to the output in series. The coupled inductor is usedas a transformer in the forward converter. When the switch isturned off, the energy of magnetic inductor Lm is released viathe secondary side of the coupled inductor to charge capacitorsC2 and C3 in parallel. The coupled inductor is used as atransformer in the flyback converter.

To simplify the circuit analysis, the following conditions areassumed.

1) Capacitors C1, C2, C3, and Co are large enough. Thus,VC1, VC2, VC3, and Vo are considered as constants in oneswitching period.

2) The power devices are ideal, but the parasitic capacitor ofthe power switch is considered.

3) The coupling coefficient of the coupled inductor k isequal to Lm/(Lm + Lk), and the turn ratio of the coupledinductor n is equal to Ns/Np.

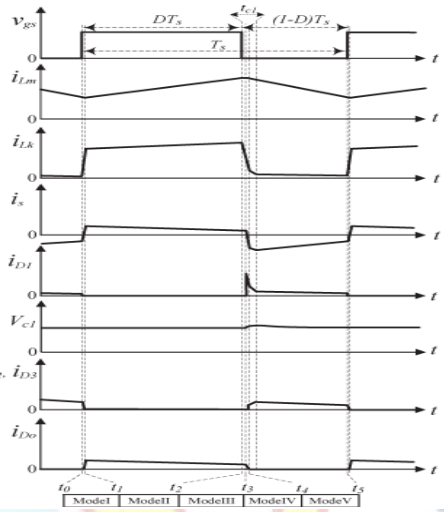


Fig 5.2: waveforms in CCM mode

5.1 CCM Operation

This section presents the operation principle of the proposedconverter. The followingnalysis contains the explanation ofthe power flow direction of each mode. In CCMoperation, thereare five operating modes in one switching period. Fig. 5.2 shows the typical waveforms, and Fig. 5.3 shows the current-flow pathof each mode of the circuit. The operating modes are described as follows.

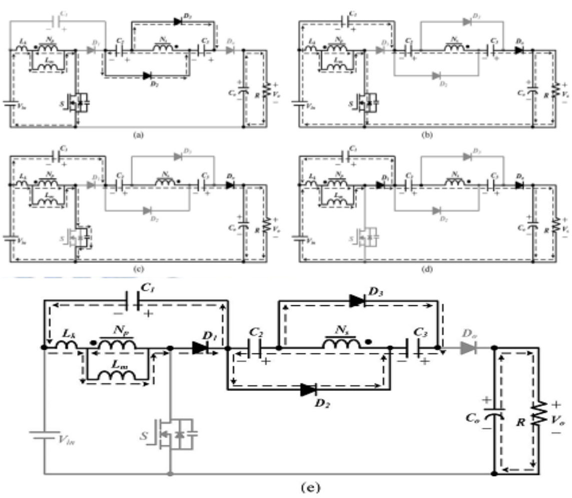


Fig 5.3:Current-flow path of operating modes during one switching period at CCM operation. (a) Mode I. (b) Mode II. (c) Mode III. (d) Mode IV. (e) Mode V

1) Mode I [t0,t1]: During this time interval, S is turned on.Diodes D1 and Do are turned off, and D2 and D3 areturned on. The current-flow path is shown in Fig. 3.9(a).The voltage equation on the leakage and magneticinductors of the coupled inductor on the primary side is expressed as Vin = VLk + VLm. The leakage inductor Lkstarts to charge by Vin. Due to the leakage inductor Lk,the secondary-side current is of the coupled inductoris decreased linearly. Output capacitor Co provides itsenergy to load R. When current iD2 becomes zero att = t1, this operating mode ends.

2) Mode II [t1,t2]: During this time interval, S remainsturned on. Diodes D1, D2, and D3 are turned off, and Dois turned on. The current-flow path is shown in Fig. 3.9(b).Magnetizing inductor Lm stores energy generated by dc-source Vin. Some of the energy of dc-source Vin transfersto the secondary side via the coupled inductor. Thus,the induced voltage VL2 on the secondary side of thecoupled inductor makes Vin, VC1, VC2, and VC3, whichare connected in series, discharge to high-voltage outputcapacitor Co and load R. This operating mode ends whenswitch S is turned off at t = t2.

3) Mode III [t2,t3]: During this time interval, S is turned off.Diodes D1, D2, and D3 are turned off, and Do is turnedon. The current-flow path is shown in Fig. 3.9(c). Theenergies of leakage inductor Lk and magnetizing inductorLm charge the parasitic capacitor Cds of main switch S.Output capacitor Co provides its energy to load R. When the capacitor voltage VC1 is equal to Vin + Vds at t = t3,diode D1 conducts, and this operating mode ends.

4) Mode IV [t3,t4]: During this time interval, S is turnedoff. Diodes D1 and Do are turned on, and D2 and D3 areturned off. The current-flow path is shown in Fig. 3.9(d).The energies of leakage inductor Lk and magnetizinginductor Lm charge clamp capacitor C1. The energy ofleakage inductor Lk is recycled. Current iLk decreasesquickly. Secondary-side voltage VL2 of the coupled inductor continues charging high-voltage output capacitorCo and load R in series until the secondary current of thecoupled inductor is equal to zero. Meanwhile, diodesD2 and D3 start to turn on. When iDo is equal to zero att = t4, this operating mode ends.

5) Mode V [t4,t5]: During this time interval, S is turnedoff. Diodes D1, D2, and D3 are turned on, and Do isturned off. The current-flow path is shown in Fig. 3.9(e).Output capacitor Co is discharged to load R. The energiesof leakage inductor Lk and magnetizing inductor Lmcharge clamp capacitor C1. Magnetizing inductor Lm isreleased via the secondary side of the coupled inductorand charges capacitors C2 and C3. Thus, capacitors C2and C3 are charged in parallel. As the energy of leak age inductor Lk charges capacitor C1, the current iLk.

VI. Model Simulation & Results

MATLAB Simulink model for the system under analysis is shown in figure 6.1.

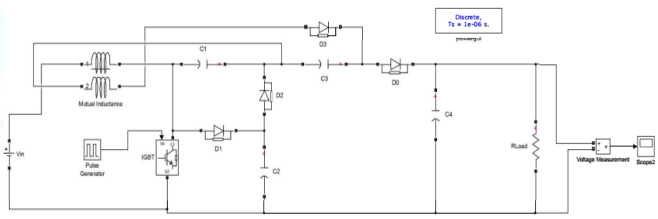


Fig 6.1: MATLAB Simulation model for the circuit under analysis.

Output of DC-DC Boost Converter

The purpose of DC – DC Converter is to provide a stabilized DC Voltage at the input terminals of the inverter. High step up gain can be obtained by using coupled inductor based dc – dc converters. In the proposed circuit a boost converter with a step up gain ratio 6 is used. Output voltage is shown in fig 6.2.

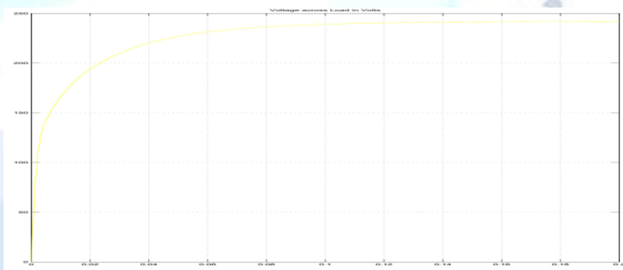


Fig 6.2:Output Voltage of DC – DC Converter.

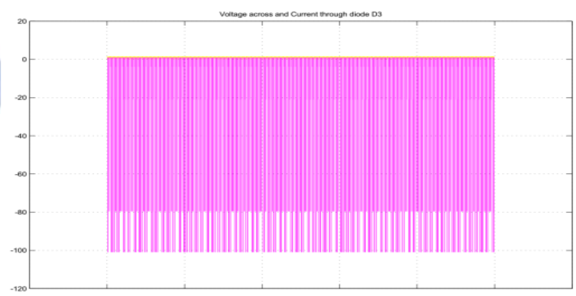


Fig 6.3:Voltage across and current through D3

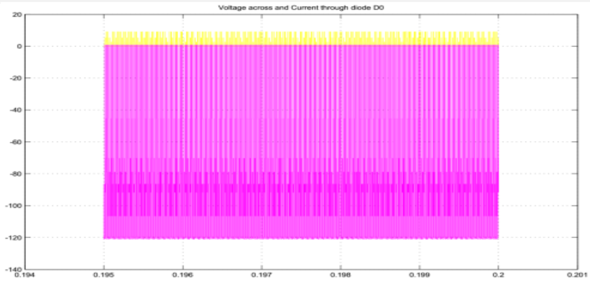


Fig 6.4:Voltage across and current through D0

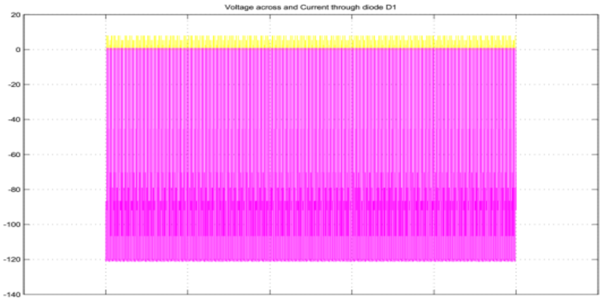


Fig 6.5: Voltage across and current through D1

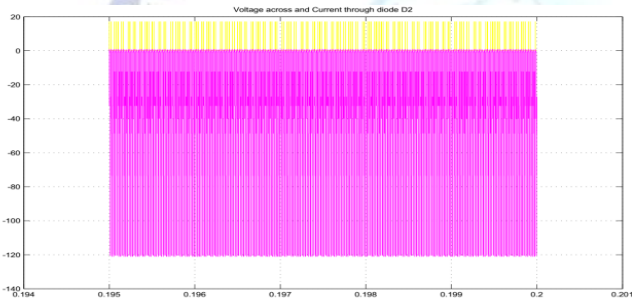


Fig 6.6: Voltage across and current through D2

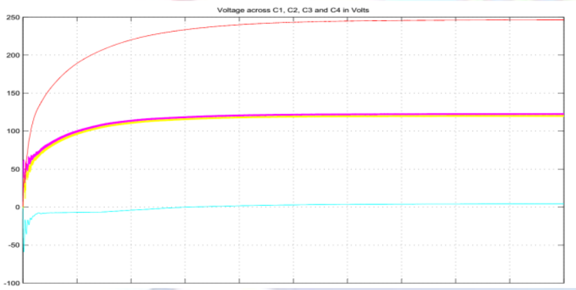


Fig 6.7: Voltage across Capacitors C1, C2, C3 and C4 in Volts

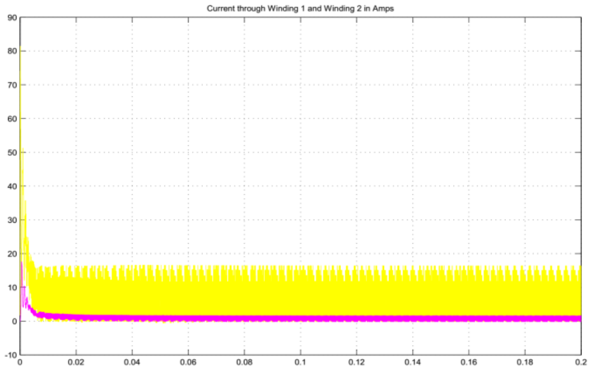


Fig 6.7:Current through coli 1 and coil 2 of coupled inductor in Amps

VII. CONCLUSION

In this paper, a novel high efficiency dc-dc converter with high voltage gain and reduced voltage stress across the switch and other circuit elements has been proposed. Operation principles and steady state analysis have been described.

Furthermore, simulations have been done to verify the performance of the proposed converter. According to Simulation results and the fact that the proposed converter can use components with low voltage ratings, it is obvious that the size and cost of the proposed dc-dc converter can be decreased.

In addition, the reverse recovery problem of the output diode has been alleviated in the proposed converter.

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