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Inductor Coupled Single-Input Multiple-Output (SIMO) DC-DC Converter

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ABSTRACT

The aim of this study is to develop a Inductor coupled single input multiple output (SIMO) dc–dc converter. The proposed converter can boost the voltage of a low-voltage input power source to a controllable high-voltage dc bus and middle-voltage output terminals. The high-voltage dc bus can take as the main power for a high-voltage dc load or the front terminal of a dc–ac inverter. Moreover, middle-voltage output terminals can supply powers for individual middle-voltage dc loads or for charging auxiliary power sources (e.g., battery modules). As a result the objectives of high-efficiency power conversion, high step up ratio, and various output voltages with different levels can be obtained.

Keywords: Inductor Coupled; High-Efficiency Power Conversion; Single-Input Multiple-Output (SIMO) Converter; Soft Switching; Voltage Clamping.

1.0 Introduction

The main objective of this project is to study the DC to DC converters in order to generate multi level DC voltages at high efficiency. The study includes designing and simulation of the circuit using MATLAB software. The simulation results will be compared and analyzed between the theoretical values and the simulation values.

In order to protect the natural environment on the earth, the development of clean energy without pollution has the major representative role in the last decade. By dealing with the issue of global warming, clean energies, such as fuel cell (FC), photovoltaic, and wind energy, etc., have been rapidly promoted. Due to the electric characteristics of clean energy, the generated power is critically affected by the climate or has slow transient responses, and the output voltage is easily influenced by load variations. Besides, other auxiliary components,, e.g., storage elements, control boards, etc., are usually required to ensure the proper operation of clean energy.

For example, an FC-generation system is one of the most efficient and effective solutions to the environmental pollution problem. In addition to the FC stack itself, some other auxiliary components, such as the balance of plant (BOP) including an electronic control board, an air compressor, and a

cooling fan, are required for the normal work of an FC generation system. Other words, the generated power of the FC stack also should satisfy the power demand for the BOP. Thus, various voltage levels should be required in the power converter of an FC generation system. In general, various single-input single-output dc-dc converters with different voltage gains are combined to satisfy the requirement of various voltage levels, so that its system control is more complicated and the corresponding cost is more expensive.

The motivation of this study is to design a single-input multiple-output (SIMO) converter for increasing the conversion efficiency and voltage gain, reducing the control complexity, and saving the manufacturing cost.

This study presents a newly designed SIMO converter with a coupled inductor. The proposed converter uses one power switch to achieve the objectives of high-efficiency power conversion, high step-up ratio, and different output voltage levels. In the proposed SIMO converter, the techniques of soft switching and voltage clamping are adopted to reduce the switching and conduction losses via the utilization of a low-voltage-rated power switch with a small RDS (on). Because the slew rate of the current change in the coupled inductor can be restricted by the leakage inductor, the current transition time

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enables the power switch to turn ON with the ZCS property easily, and the effect of the leakage inductor can alleviate the losses caused by the reverse-recovery current.

Fig 1: Block Diagram Of Inductor Coupled Single-Input Multiple-Output (SIMO) DC-DC Converter
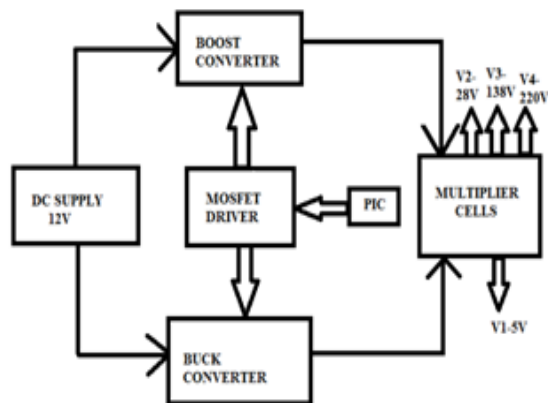
Additionally, the problems of the stray inductance energy and reverse-recovery currents within diodes in the conventional boost converter also can be solved, so that the high-efficiency power conversion can be achieved. The voltages of middle-voltage output terminals can be appropriately adjusted by the design of auxiliary inductors; the output voltage of the high-voltage dc bus can be stably controlled by a simple proportional-integral (PI) control.

In fig1.DC-DC converter is used to convert the fixed DC to Variable DC. The variable DC may be either low or high, depending upon application and power factor it may varied. The output of the converter is directly to load and when applied to the load it may lagging or Leading power. In lag power, IGBT thyristor are used which as low switching speed and high input impedance whereas for leading, MOSFET acts switching which as high switching speed and output impendence is high compared to lag power.

In Zero Current Switching (ZCS) technique and the function is realized so that the power form is converted from 12V DC to 5V DC (1A). A detailed analysis of zero current switching converters is performed and a mathematical analysis of the mode of operation is also presented.

In order to reduce the switching losses in associated with conventional converters; resonant inductor and resonant capacitor (LC resonant circuit) is applied which helps to turn on-off the switch at zero current. This work focuses on the issues related with the designing of ZCS converter. The main objective of the work is to append zero current switching techniques.

This study presents a newly designed SIMO converter with a coupled inductor.

The proposed converter uses one power switch to achieve the objectives of high-efficiency power conversion, high step-up ratio, and different output voltage levels. In the proposed SIMO converter, the techniques of soft switching and voltage clamping are adopted to reduce the switching and conduction losses via the utilization of a low-voltage-rated power switch with a small RDS (on).

Because the slew rate of the current change in the coupled inductor can be restricted by the leakage inductor, the current transition time enables the power switch to turn ON with the ZCS property easily, and the effect of the leakage inductor can alleviate the losses caused by the reverse-recovery current.

Additionally, the problems of the stray inductance energy and reverse-recovery currents within diodes in the conventional boost converter also can be solved, so that the high-efficiency power conversion can be achieved.

The voltages of middle-voltage output terminals can be appropriately adjusted by the design of auxiliary inductors; the output voltage of the high-voltage dc bus can be stably controlled by a simple proportional-integral (PI) control.

But in the proposed method both Buck and Boost converter techniques are used hence it is capable of generating both Buck and Boost outputs simultaneously. With the help of Buck converter of voltages are obtained similarly in the boost converter section three different kind of voltages are generated.

Various techniques such as zero current switching, coupled inductance and other methods are utilized in order to get the required output.

Proposed method is designed in order to use the high efficiency multilevel DC to DC converter for various low power applications such as LVDS, micro controller circuits and other USB voltage level input devices.

Moreover, middle-voltage output terminals can supply powers for individual middle-voltage dc loads or for charging auxiliary power sources.

2.0 Circuit Diagram

Fig 2: Circuit Diagram Of Inductor Coupled Single-Input Multiple-Output (SIMO) DC-Dcconverter
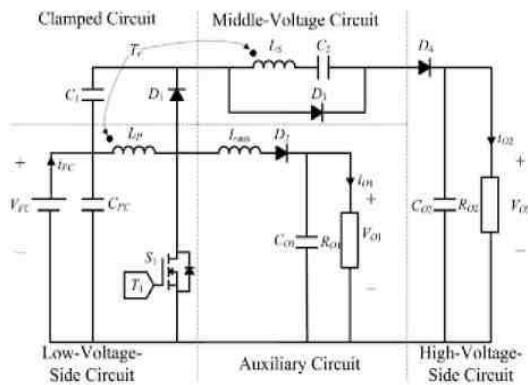
Basic circuit diagram of the project is represented as follows basic sections that are present in the circuit is explained with the help of the following circuit.

This SIMO converter contains five parts including a low-voltage-side circuit (LVSC), a clamped circuit, a middle-voltage circuit, an auxiliary circuit, and a high-voltage-side circuit (HVSC).

The major symbol representations are summarized as follows. VFC (iFC) and VOl (iOl) denote the voltages (currents) of the input power source and the output load at the LVSC and the auxiliary circuit, respectively; V02 and i02 are the output voltage and current in the HVSC. CFC, CO , and C02 are the filter capacitors at the LVSC, the auxiliary circuit, and the HVSC, respectively;Cl and C2 are the clamped and middle-voltage capacitors in the clamped and middle-voltage circuits, respectively.

LP and LS represent individual inductors in the primary and secondary sides of the coupled inductor Tr, respectively, where the primary side is connected to the input power source; Laux is the auxiliary circuit inductor.

The main switch is expressed as SI in the LVSC; the equivalent load in the auxiliary circuit is represented as ROl , and the output load is represented as RO 2 in the HVSC. The corresponding

equivalent circuit given in Figure is used to define the voltage polarities and current directions.

The inductor coupled in figure 2 can be modeled as an ideal transformer including the magnetizing inductor Lmp and the leakage inductor L in Figure The turns ratio N and coupling coefficient k of Figure Equivalent circuit.

This ideal transformer are defined as

N = N2/N1

k = Lmp/(Lkp + Lmp)= Lmp/LP

Where Nl and N2 are the winding turns in the primary and secondary sides of the coupled inductor Tr .Because the voltage gain is less sensitive to the coupling coefficient and the clamped capacitor CI is appropriately selected to completely absorb the leakage inductor energy , the coupling coefficient could be simply set at one (k = 1) to obtain Lmp = LP. In this study, the following assumptions are made to simplify the converter analyses are The main switch including its body diode is assumed to be an ideal switching element and the conduction voltage drops of the switch and diodes are neglected.

Four different levels of output voltages are obtained with the help of proposed method, which are represented in the following table, output levels are represented in DC. In the following table the voltage levels vl are obtained with the help of buck converter circuit and the voltage levels v2, v3 and v4 are obtained with help of coupled inductor based Boost converter.

3.0 Principle of Operation

The characteristic waveforms and the topological modes in one switching cycle are illustrated in following Figure.

### Fig 3: Proposed System Characteristics Curve
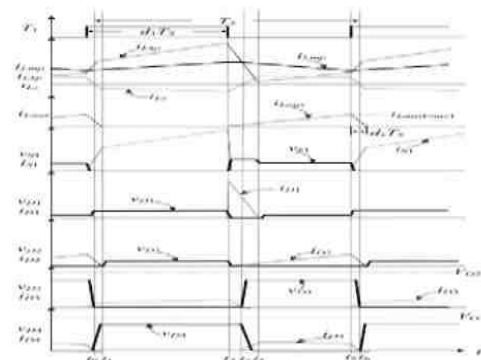
1) **Model (tO-tl):** In this mode, the main switch SI was turned ON for a span, and the diodeD4 turned OFF. Because the polarity of the windings of the coupled inductor Tr is positive, the diode D3 turns ON. The secondary current iLs reverses and charges to the middle voltage capacitorC2. When the auxiliary inductor Laux releases its stored energy completely, and the diode D2 turns OFF, this mode ends.

2) **Mode 2 (tl-t2):** At time t =tl, the main switch Slis persistently turned ON. Because the primary inductor LP is charged by the input power source, the magnetizing current iLmp increases gradually in an approximately linear way. At the same time, the secondary voltage vLs charges the middle-voltage capacitorC2through the diode D3. Although the voltage vLmp is equal to the input voltage VFC both at modes 1 and 2, the ascendant slope of the leakage current of the coupled inductor (diLkp/dt) at modes 1 and 2 is different due to the path of the auxiliary circuit.

3) **Mode 3 (t2-t3):** At time t=t2, the main switch SI is turned OFF. When the leakage energy still released from the secondary side of the coupled inductor, the diode D3 persistently conducts and releases the leakage energy to the middle-voltage capacitor C2. When the voltage across the main switchvSl is higher than the voltage across the clamped capacitor VC1, the diode Dl conducts to transmit the energy of the primary-side leakage inductor Lkp into the clamped capacitorCl. At the same time, partial energy of the primary-side leakage inductor Lkp is transmitted to the auxiliary inductor Laux, and the diode D2 conducts. Thus, the current iLaux passes through the diode D2 to supply the power for the output load in the auxiliary circuit. When the secondary side of the coupled inductor releases its leakage energy completely, and the diode D3 turns OFF, this mode ends.

4) **Mode 4 (t3-t4):** At time t=t3, the main switch SI is persistently turned OFF. When the leakage energy has released from the primary side of the coupled inductor, the secondary current iLS is induced in reverse from the energy of the magnetizing inductor Lmp through the ideal transformer, and flows through the diode D4 to the HVSC. At the same time, partial energy of the primary side leakage inductor Lkp is still persistently transmitted to the auxiliary inductor Laux, and the diode D2 keeps to conduct. Moreover, the current iLaux passes through the diodeD2 to supply the power for the output load in the auxiliary circuit.

5) **Mode 5 (t4-t5):** At time t=t4, the main switch SI is persistently turned FF, and the clamped diodeDl turns OFF because the primary leakage current iLkp equals to the auxiliary inductor current iLaux. In this mode, the input power source, the primary winding of the coupled inductor Tr, and the auxiliary inductor Laux connect in series to supply the power for the output load in the auxiliary circuit through the diodeD2. At the same time, the input power source, the secondary winding of the coupled inductor Tr, the clamped capacitor CI, and the middle voltage capacitor (C2) connect in series to release the energy into the HVSC through the diode D4.

6) **Mode 6 (t5-t6):** At time t=t5, this mode begins when the main switchSl is triggered. The auxiliary inductor current Laux needs time to decay to zero, the diode D2 persistently conducts. In this mode, the input power source, the clamped capacitorCl, the secondary winding of the coupled inductor Tr, and the middle-voltage capacitorC2 still connect in series to release the energy into the HVSC through the diodeD4. Since the clamped diodeDl can be selected as a low voltage Schottky diode, it will be cut off promptly without a reverse-recovery current. Moreover, the rising rate of the primary current Lkp is limited by the primary-side leakage inductor Lkp. Thus, one cannot derive any currents from the paths of the HVSC, the middle-voltage circuit, the auxiliary circuit, and the clamped circuit.

As a result, the main switch SI is turned ON under the condition of ZCS and this soft-switching property is helpful for alleviating the switching loss. When the secondary current LS decay to zero, this mode ends.

After that, it begins the next switching cycle and repeats the operation in mode.

4.0 System Efficiency

Fig 4: System Efficiency Curves
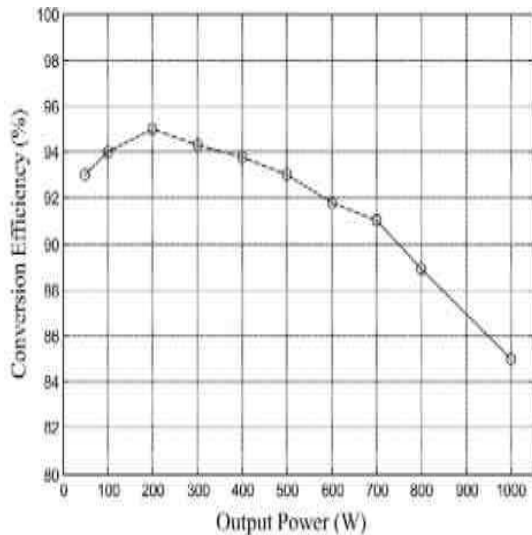
Efficiency curve of the proposed converter is given in Fig. 4.2. the proposed SIMO converter utilizes the property of the coupled inductor to make the switch working at ZCS, to raise the voltage gain, and to alleviate the reverse-recovery current, so that higher conversion efficiency and voltage gain can be obtained in comparison with the combination of two traditional boost converters.

Moreover, it is easy to extend the output terminals of the proposed SIMO converter by adding auxiliary circuits, not a complete structure of traditional boost converter circuit.

As long as the well designs of auxiliary inductors according to the figure regulation of output voltages also can be achieved.

As a result, the functions of the proposed SIMO converter with high-conversion efficiency, high-voltage gain and low-manufacturing cost are superior to the combination of traditional single-input single-output converters.

5.0 Voltage Gain Derivation

The magnetizing inductor voltage vLmpis equal to the input power source VFC, the voltage can be represented as

$$vLmp = VFC \dots (1)$$

Due to the relation of vLs=NvLp=VC2, the voltage VC2 can be represented as

$$VC2 = NVFC. \dots (2)$$

By using the voltage-second balance, the relation of the average voltage across the magnetizing inductor Lmpof the coupled inductor Trto be zero can be represented as

$$VFCd1TS + vLmp(1 - d1)TS = 0 \dots (3)$$

From (3), one can obtain

$$vLmp = [-d1/(1 - d1)]VFC \dots (4)$$

Since the voltage of the clamped capacitor VC1 is equal to the negative voltage of magnetizing inductors voltage vLmp, the voltage VC1 can be expressed via (4) as

$$VC1 = -vLmp = [d1/(1 - d1)]VFC \dots (5)$$

According to Kirchhoff's voltage law, the output voltage VO2 can be obtained as

$$VO2 = VFC + VC1 + VC2 - vLs \dots (6)$$

By using the voltage-second balance, the relation of the average voltage across the secondary winding vLsto be zero can be expressed by (2) and (6) as

$$(NVFC) d1TS + (VFC + VC1 + VC2 - VO2)(1 - d1)TS = 0 \dots (7)$$

Voltage gain Gv1 = V01/Vfc

$$= 2/((1 - d1)\sqrt{(1 - d1)^2 + [8Laux/(RO1TS)]}$$

6.0 Methods to Achieve High Efficiency

In order to achieve high efficiency in DC to DC voltage conversion various methods are adopted in this project they are listed as follows.

The Switching transitions occur under favorable conditions - device voltage or current is zero, Reduced switching losses, switch stress, possibly low EMI, easier thermal management, A must for very high frequency operation (also medium frequency at high power levels), Usually involves compromises in conduction loss, switch rating, passive components etc. Types of soft switching are

- ZVS (Zero Voltage Switching)
- ZCS (Zero Current Switching)

Advantages of soft switching

Soft switching technique is mainly used in DC-DC converters to mainly achieve following factors.

- Lower losses
- Low EMI
- Allows high frequency operation

The synchronizing of the operation of semiconductor switches in (resonant) power converters with the natural zero-crossing of the current flowing in the converter's power circuit. Results in near-lossless switching, permitting increases in switching frequency required to enable eduction in transfer

Figure 5 zero current switching Diagram

ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on.

As a relatively large capacitor is connected across the output diode during resonance, the converter operation becomes insensitive to the diode's junction capacitance. The major limitations associated with ZCS when power mosfet are used are the capacitive turn-on losses. Thus, the switching loss is proportional to the switching frequency. During turn-on, considerable rate of change of voltage can be coupled to the gate drive circuit through the Mller capacitor, thus increasing switching loss and noise. Another limitation is that the switches are under high current stress, resulting in high conduction loss.

It should be noted that ZCS is particularly effective in reducing switching loss for power devices (such as IGBT) with large tail current in the turn-off process.

ZVS eliminates the capacitive turn-on loss. It is suitable for high-frequency operation. For single-ended configuration, the switches could suffer from excessive voltage stress, which is proportional to the load. It will be that the maximum voltage across switches in half-bridge and full-bridge configurations is clamped to the input voltage.

For both ZCS and ZVS, output regulation of the resonant converters can be achieved by variable frequency control. ZCS operates with constant on-time control, while ZVS operates with constant off-time control.

With a wide input and load range, both techniques have to operate with a wide switching frequency range, making it not easy to design resonant converters optimally.

Advantages of using Zero current switching in DC-DC converters during Turn ON and turn OFF stages are

- Turn ON
- Switch current brought to zero before gate voltage is
- removed
- Ideal, zero-loss transition
- Turn OFF
- Low-loss transition
- Series inductor as a loss-less snubber
- Energy in junction capacitance is lost

Today, every microprocessor is powered by a multilevel voltage regulator (VR).

Each level employs a sizeable energy storage inductor to perform the necessary power conversion.

For such an application, a larger inductance is preferred for steady-state operation, so that the current ripples can be reduced.

On the other hand, a smaller inductor is preferred for fast transients, such as from "sleep-mode" to "wake-up mode" and vice versa.

To satisfy this conflicting requirement, a nonlinear inductor, in principle, would be preferred so that during the steady state, the inductance value is large, while during the transient state, the inductance value is small.

However, there is no simple way of realizing such a nonlinear inductor.

When the inductors are coupled in a multi-level buck converter, by virtue of magnetic coupling in the switching network, they behave like nonlinear inductors.

Fig 6: Coupled inductor in DC to DC converter
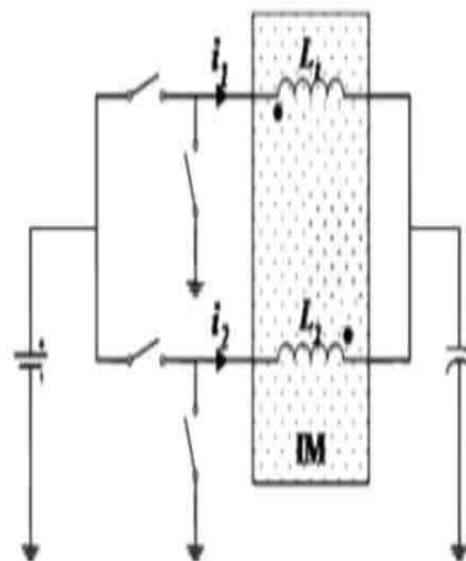
The equivalent inductance is large for a steady state and small for a transient. This enables multi-level VR to deliver power more effectively to the microprocessor that is currently operating at GHz clock frequency.

This proposed coupled-inductor concept enables much improved performance, resulting in reduced footprint and cost.

The alternative solution to the coupled-inductor approach is to use a large number of decoupling capacitors to supply the transient power needed for the computer, which is cost prohibitive.

## 7.0 Simulink Model of high Efficiency Dc - Dc SIMO Converter
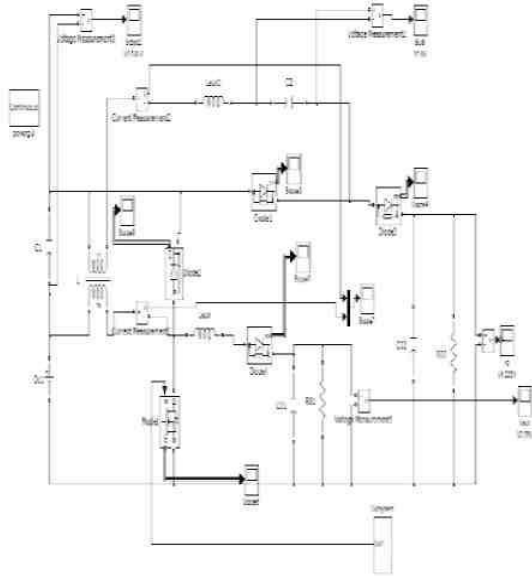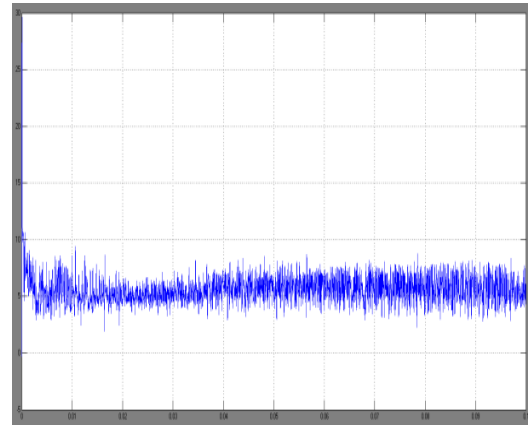

8.0 Output Voltages

Presented SIMO dc-dc converter capable of generating buck and boost outputs simultaneously, voltage levels of both the methods are represented as follows with the help of simulation waveforms.

The waveforms of VI, V2, V3 and V4 represents the output voltage levels of Buck converter which are 5v. Similarly the waveforms of V2, V3 and V4 represents the output voltage levels of boost converter which are 28V, 138V and 220V voltages respectively.
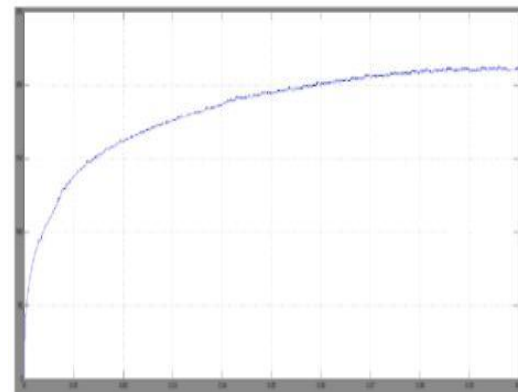
Fig 10: Output voltage V2 wave form
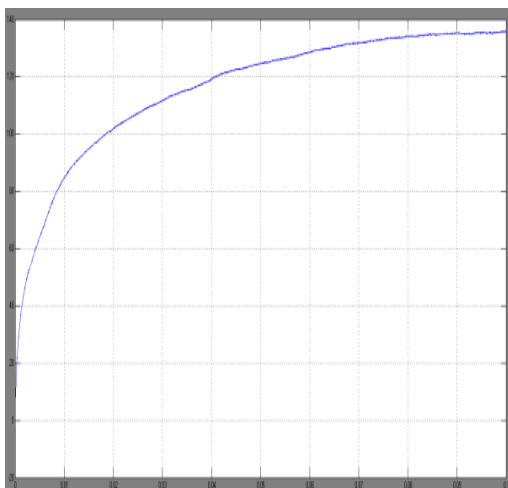
Fig 11: Output Voltage V3 Wave form

Fig 12: Output voltage V4 wave form

9.0 Applications of Proposed Method

Low-voltage differential signaling, or LVDS, is an electrical digital signaling standard that can run at very high speeds over inexpensive twisted-pair copper cables, The low common-mode voltage (the average of the voltages on the two wires) of about 1.2V allows using LVDS with a wide range of integrated circuits with power supply voltages down to 2.5 V or lower.

LVDS is not the only differential signaling system in use, but is currently the only scheme that combines low power dissipation with high speed. Switched-mode power supplies have applications in various areas. A switched-mode supply is chosen for an application when its weight, efficiency, size, or wide input range tolerance make it preferable to linear power supplies. Initially the cost of semiconductors made switch-mode supplies a premium cost alternative, but current production

switch-mode supplies are nearly always lower in cost than the equivalent linear power supply.

Other consumer applications of this converter are Personal computers, Battery chargers, Central power distribution, Vehicles, Consumer electronics, Lighting, Space station and more.

10.0 Conclusion

The proposed SIMO converter utilizes the property of the coupled inductor to make the switch working at ZCS, to raise the voltage gain, and to alleviate the reverse-recovery current, so that higher conversion efficiency and voltage gain can be obtained in comparison with the combination of two traditional boost converters.

Moreover, it is easy to extend the output terminals of the proposed SIMO converter by adding auxiliary circuits, not a complete structure of traditional boost converter circuit.

As long as the well design of auxiliary inductors according to the regulation of output voltages also can be achieved.

As a result, the functions of the proposed SIMO converter with high-conversion efficiency, high-voltage gain and low-manufacturing cost are superior to the combination of traditional single-input single-output converters.

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