A Closed Loop Control of Modified SEPIC Converter for Renewable Applications

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***Abstract*— *The high static gain step-up DC-DC converters based on the modified SEPIC converter are presented in this paper. The proposed topologies present low switch voltage and high efficiency for low input voltage and high output voltage applications. The configurations with magnetic coupling is presented and analyzed. The magnetic coupling allows the increase of the static gain maintaining a reduced switch voltage. The theoretical analysis and structures is suitable for high static gain applications as a renewable power sources with low DC output voltage. Simulation model is developed with an input voltage equal to 15 V and an output power equal to 100 W. The prototype with magnetic coupling operating with an output voltage equal to 300 V, presents efficiency at nominal power equal to 92.2%. PI controller based triggering system is developed for Modified SEPIC converter to maintain constant output voltage.*

Keywords—Renewable energy and automobile application.

1. INTRODUCTION (*DC-DC CONVERTER 1*)

A DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. It is a class of power converter. Most DC to DC converters also regulate the output voltage. Some exceptions include high-efficiency LED power sources, which are a kind of DC to DC converter that regulates the current through the LEDs, and simple charge pumps which double or triple the output voltage. The open loop usage in the circuit will result in variation in supply output which causes many difficulties. This paper is discussed to rectify that problem. This paper presents a high gain and high efficiency converter to provide the constant output voltage and to reduce the voltage stress.

2. RENEWABLE ENERGY

Renewable energy is generally defined as energy that comes from resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat. Renewable energy replaces conventional fuels in four distinct areas: electricity generation, air and water heating/cooling, motor fuels, and rural (off-grid) energy services. Wind, solar, and biomass are three emerging renewable sources of energy.

II. CLOSED LOOP CONTROL OF MODIFIED SEPIC CONVERTER

2.1 OPERATION

To maintain the output voltage constant in spite of changes in input voltage a feedback closed loop control is necessary. A Modified Single-Ended-Primary-Inductor (Mod SEPIC) Converter is a kind of dc- dc converter which allows the electrical potential (voltage) at its output to be greater than, less than, or even equal to that of its input. SEPIC is controlled by the duty cycle of the control switch. Closed loop model of modified SEPIC converter is proposed in this system. In open loop converters, output has no effect on input to control a process. But the key features to be satisfied by a converter are to measure and control a process. So in order to control a process for having a desired response, the actual output should be compared with the desired one and thus generated quantity can be used as input to the converter. And the same happens in a closed loop converter.

2.2 BLOCK DIAGRAM

From the figure 2.1 the Block Diagram of Closed Loop Modified SEPIC Converter the voltage sensor is used to measure the voltage of modified SEPIC converter. In short, the actual process that occurs in a closed loop converter is the error signal which is the difference between input and feedback signal (output or a function of output) is given to the PI controller to obtain the output at a desired value. The output of PI controller is duty cycle is given to modified SEPIC converter. So it is well clear that the main disadvantage for an open loop system is the output voltage variation along with the input voltage changes. Hence it would be difficult to limit the output voltage as per our intention. In order to limit the output voltage to a desired value (fixed voltage) it is better to use a closed loop system.

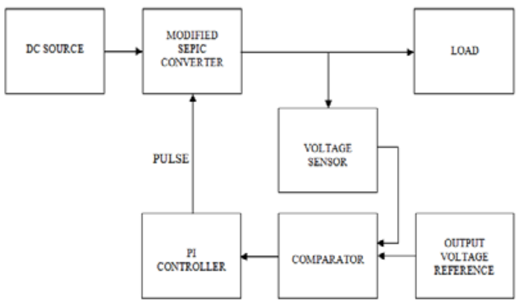


Fig. 2.1 Block Diagram of Closed Loop Modified SEPIC Converter

2.3 MODIFIED SEPIC CONVERTER WITH MAGNETIC COUPLING

The modified SEPIC converter without magnetic coupling can operate with the double of the static gain of the classical boost converter for a high duty-cycle operation. However, a very high static gain is necessary in some applications. A practical limitation for the modified SEPIC converter in order to maintain the converter performance is a duty-cycle close to D=0.85, resulting in a maximum static gain equal to q=12.3. A simple solution to elevate the static gain without increases the duty-cycle and the switch voltage is to include a secondary winding in the L_2 inductor. The L_2 inductor operation is similar to a buck-boost inductor and a secondary winding can increases the output voltage by the inductor windings turns ratio (n), operating as a flyback transformer.

However, this converter structure presents the problem of overvoltage at the output diode Dodue to the existence of the coupling winding L_2 leakage inductance. The energy stored in the leakage inductance, due to the reverse recovery current of the output diode, results in voltage ring and high reverse voltage at the diode Do. This overvoltage is not easily controlled with classical snubbers or dissipative clamping. A simple solution for this problem is the inclusion of a voltage multiplier at the secondary side as presented in Figure 2.2.

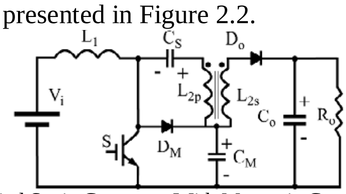


Fig. 2.2 Modified Sepic Converter With Magnetic Coupling

This voltage multiplier increases the converter static gain, the voltage across the output diode is reduced to a value lower than the output voltage and the energy stored in the leakage inductance is transferred to the output. Therefore the secondary voltage multiplier composedby the diode D_{M2} and capacitor C_{S2} is also a non-dissipative clamping circuit for the output diode. The circuit presented in Fig. 3.8 is the power circuit studied in this paper

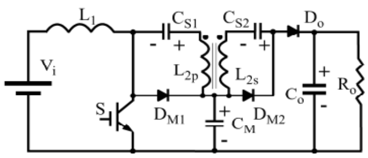


Fig. 2.3 Proposed Converter Modified Sepic Converterwith Magnetic Coupling

The solutions based on the classical boost converter with magnetic coupling or the integration of the magnetic coupling and the voltage multiplier cell can present very high voltage gain and an excellent performance as presented . However, as the magnetic coupling is accomplished with the input inductor in the boost based solutions, the input current ripple is significantly increased and depends on the inductor winding turns ratio. Increasing the inductor turns ratio and the static gain, the input current ripple rises. The input current ripple increment is a non desirable operation characteristic for some applications as the fuel cell power source. As the magnetic coupling is not accomplished with the input inductor in the topology, the input current ripple is low and is not changed by the magnetic coupling.

1. Five Stage Operation of Modified SEPIC converter with magnetic coupling

The continuous conduction mode operation of the modified SEPIC converter with magnetic coupling and output diode clamping presents five operation stages. All capacitors are considered as a voltage source and the semiconductors are considered ideals for the theoretical analysis.

First Stage [T_0 - T_1]

From the figure 2.2. The power switch S is conducting and the input inductor L_1 stores energy.

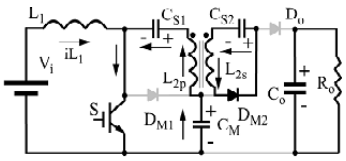


Fig. 2.4 First Stage

The capacitor C_{S2} is charged by the secondary winding Ls_2 and diode D_{M2}. The leakage inductance limits the current and theenergy transference occurs in a resonant way. The outputdiode is blocked and the maximum diode voltage is equal to (Vo-VCM) At the instant t_1 the energy transference to the capacitor C_{S2} is finished and the diode DM_2 is blocked.

Second Stage [T_1 -T_2]

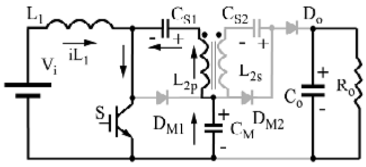


Fig. 2.5 Second Stage

From the figure 2.5. From the instant t_1, when the diode D_{M2} is blocked, to the instant t_2 when the power switch is turned off, the inductors L_1 and L_2 store energy and the currents linearly increase.

Third Stage [T_2 - T_3]

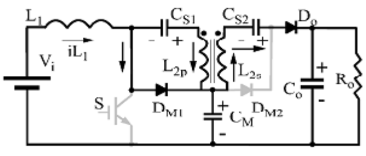


Fig. 2.6 Third Stage

From the figure 2.6. At the instant t_2 the power switch S is turned off. The energy stored in the L_1 inductor is transferred to the CM capacitor. Also there is the energy transference to the output thought the capacitors C_{S1}, C_{S2}inductor L_2 and output diode Do.

Fourth Stage [T_3 - T_4]

From the figure 2.7. At the instant t_3, the energy transference to the capacitor C_M is finished and the diode $D_{M1}$is blocked.

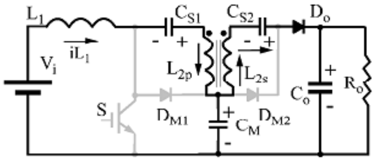


Fig. 2.7 Fourth Stage

The energy transference to the output is maintained until the instant t_4, when the power switch is turned on.

Fifth Stage [T_4 - T_5]

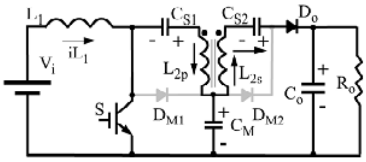


Fig.2.8 Fifth Stage

From the figure 2.8. When the power switch is turned on at the instant t_4, the current at the output diode Do linearly decreases and the di/dtis limited by the transformer leakage inductance, reducing the diode reverse recovery current problems. When the output diode is blocked, the converter returns to the first operation stage.

Theoritical Waveform

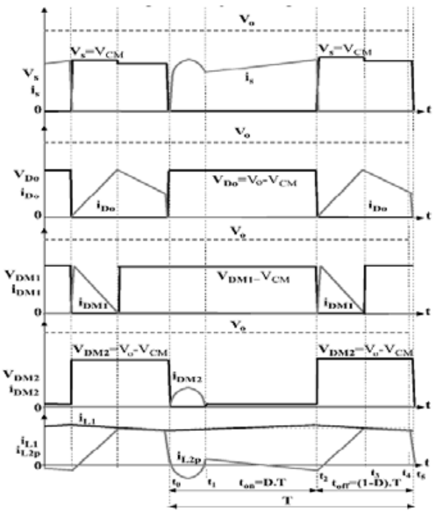


Fig. 2.9 Main Theoretical Waveforms of The Modified Sepic Converter With Magnetic Coupling

From the waveform he switch voltage and the voltage across all diodes are lower than the output voltage. The power switch turn on occurs with almost zero current reducing significantly theswitching losses. The current variation ratio (di/dt) presented by all diodes is limited due to the presence of the coupling inductor leakage inductance, reducing the negative effects of the diode reverse recovery current. The static gain of the modified SEPIC converter with magnetic coupling and voltage multiplier is calculated by equation (2.1). The static gain can be increased by the windings turns ratio (n) without increasing the switch voltage.

$$\frac{V0}{Vi} = \frac{1}{1-D} \cdot (1+n) \quad (2.1)$$

Where the inductor windings turns ratio (n) is calculated by:

$$n = \frac{NL2s}{NL2p} \quad (2.2)$$

Considering a duty-cycle equal to 0.8, a static gain equal to q= 10 is obtained for n=1, q=15 for n=2 and q=20for n=3 and the switch voltage is equal to five times the input voltage for all cases. The static gain variation as a function of the duty-cycle is presented in Figure 2.10.

The third operation stage, presented in above Figure, determinates the maximum switch voltage. Therefore, the maximum switch voltage is equal to the capacitor C_M voltage calculated and it is the lowest curve presented .

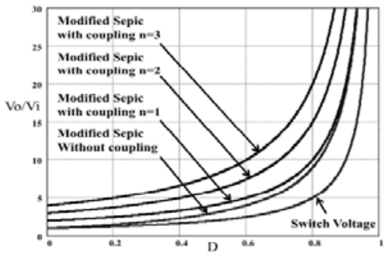


Fig. 2.10 Staticgain Variation as a Function of the Duty-cycle and Transform Turns Ratio

During the fourth operation stage presented, the switch voltage presents a small reduction from calculated, as presente at the interval (t_3-t_4). The voltage across the leakage inductance must be reduced from the voltage calculated during the fourth operation stage and this voltage reduction is proportional tothe relation between the leakage inductance of the coupling inductor L_2p-L_2s and the input inductance L_1.

2. Design Considaration Of Mod SEPIC Converter With Magnetic Coupling

The main equations to design the modified SEPIC converter with magnetic coupling presented in Figure 9 are shown with an example, considering the following specifications:

Output Power: Po = 100 W , Input Voltage: Vi = 15 V , Output Voltage: Vo = 300V

Switching Frequency: f = 24 kHz

Switch Duty-Cycle

Considering a static gain equal to 20 and an inductor winding turns ratio equal to n=2.6, the nominal converter duty-cycle obtained from above equation (2.3) is equal to:

$$D = 1- \frac{Vi}{V0} \cdot (1+n) = 1- \frac{15}{300} \cdot (1+2.6) = 0.819 \quad (2.3)$$

The nominal operation point is approximately the same of the topology without magnetic coupling but with a winding turns ratio equal to n=2.6, the static gain is equal to Vo/Vi=20.

Switch and Diodes Voltages

The switch voltage (Vs) and the voltage across the diode $D_{M1}$are equal the voltage of the capacitor C_M.

$$V_S = V_{DM1} = \frac{Vi}{1-D}.Vi = \frac{15}{1-0.819} = 82.9V \quad (2.4)$$

The diode D_{M2} voltage (V_{DM2}) and the output diode voltage (V_{Do}) are equal and are calculated by equation (2.4).

$$V_{D0} = V_{DM2} = V_0 - V_{CM}$$

$$= \frac{n.Vi}{1-D} = \frac{2.6.15}{1-0.819} = 215.5V \quad (2.5)$$

L_1 And L_2p-L_2s Inductance

The current ripple (iL) of the inductors L_1 and L $_2$p are calculated by the same of the topology without magnetic coupling. As the input voltage and the converter duty-cycle of the converters with and without magnetic coupling are the same, the inductance values for the magnetic coupling converter are the same presented in L_1=L_2 p=102 µH. However, the L_2 inductor presents a secondary winding L_2s for the magnetic coupling converter. Considering the windings turns ratio equal to n=2.6, the L2Sinductance is equal to:

$$L_{2S} = n^2 .L_{2P} = 2.6^2 .102.10^{-6} = 689.52\mu H \quad (2.6)$$

Leakage Inductance Lr

The leakage inductance is an intrinsic parameter of the transformer composed by the coupling inductor L_2p-L_2s. This inductance is not represented in the circuit of the converter presented or in the operation stages presented, but this inductance can be considered in series with the L_2p inductor or referred to the secondary side in series with the L_2s inductor. This inductance is very important for the reduction of the reverse recovery current of the output diode and also in order to obtain Z_{CS} switch turn-on commutation.

Using a conventional ultra-fast diode as output diode (Do) and considering null the leakage inductance, when the switch S is turned-on at the instant t_4, that is the fifth operation stage presented. , the output diode di/dt will be very high and the diode reverse recovery current will occurs increasing the commutation losses. With the inclusion of a leakage inductance, the voltage applied across the leakage inductance referred to the primary side at the switch turn-on is approximately equal to equation (2.6) and the limitation of the di/dt in the output diode by the leakage inductance is calculated by equation (2.7).

$$\frac{di}{dt} = \frac{Vi}{(1-D).Lr.n} \quad (2.7)$$

Therefore, considering a maximum di/dtequal to 25 A/µs [5], the minimum value of the leakage inductance is calculated by equation (2.8).

$$Lr = \frac{Vi}{(1-D).\frac{di}{dt}.n} = \frac{15}{(1-0.819).25.10^6.26} = 1.27\mu F \quad (2.8)$$

The half resonance period (Tres) at first operation stage, where occurs the energy transference to the capacitor CS2through the diode D_{M2} as presented and represented by the interval (t_0-t_1), is calculatd.by (3.22). As the leakage inductance Lr and the capacitors $C_{S1}$and C_{S2} present relative low values, the half resonant period is only a part of the switching period (T).

$$Tres = \pi.\sqrt{Lr.\left(\frac{Cs1.Cs2}{Cs1=Cs2}\right)} \quad (2.9)$$

Capacitors Cs And Cm

The voltage ripple of the capacitor C_{S2} is calculated by the same. The converter without magnetic coupling. The capacitors C_{S1} and C_M present the same voltage ripple and are calculated by the equation (2.1) multiplied by the inductor windings turns ratio (n), as presented in equation (2.10), considering a capacitor voltage ripple ΔVC equal to 15% of the nominal voltage of the C_M capacitor .

$$C_{S1} = C_M = \frac{I0.n}{\Delta Vc.f} = \frac{0.333.2.6}{12.4.24.10^3} = 2.9\ \mu F \quad (2.10)$$

Where

$$\Delta V_C = \left(\frac{Vi}{1-D}\right).\frac{15}{100} = \left(\frac{15}{1-0.819}\right).\frac{15}{100} = 2.9\ \mu F \quad (2.11)$$

Semiconductor Current Effort

The average current of all diodes are approximatelyequal to the output curre

$$I_{D0} = I_{DM1} = I_{DM2} = I_0 = \frac{P0}{V0} = \frac{100}{300} = 0.333\ A \quad (2.12)$$

The switch current waveform is presented in the figure 2.9. The RMS switch current can be calculated approximately by the same equation presented for the proposed converter without magnetic coupling , neglecting the additional resonant current contribution presented in the period (t_0-t_1) .

III. PI CONTROLLER FOR MODIFIED SEPIC CONVERTER

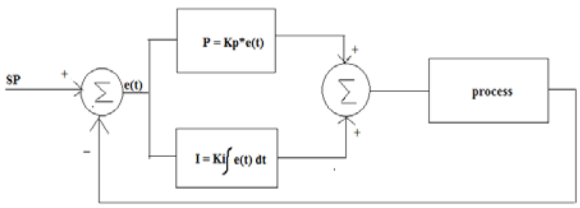


Fig. 4.1 PI Controller block Diagram

A PI Controller (Proportional-Integral Controller) is a special case of the PID controller in which the derivative (D) of the error is not used.

The controller output is given by

$$U = Kp\ \Delta + Ki \int \Delta\ dt$$

Where

Δ is the error or deviation of actual Measured Value (*PV*) from the Set-Point (*SP*).

Δ=SP-PV.

A PI controller can be modelled easily in software such as simulink using a "flow chart" box involving Laplace operators:

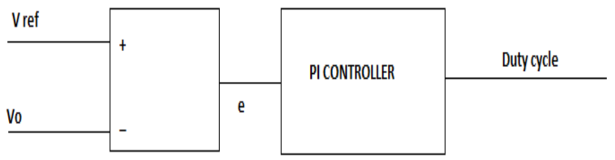
$$C = \frac{G\,(1+TS)}{TS}$$

Where

G = Kp = proportional gain,

G/t = K_1= integral gain

Setting a value for G is often a tradeoff between decreasing overshoot and increasing settling time. The lack of derivative action may make the system more steady in the steady state in the case of noisy data. This is because derivative action is more sensitive to higher-frequency terms in the inputs. The PI cotroller based modified SEPIC converter is to maintain the output voltage, it was PI controller is proposed in this project.



Δ = Vo ref – Vo

Duty ratio = Kp Δ + Ki ∫ Δ

The PI controller varies converter duty ratio to maintain output voltage as constant. The duty ratio is varied with respect to change in input voltage with the help of PI controller.

IV. SIMULATION FOR THE PROPOSED SYSTEM

Here the Modified SEPIC converter in a closed loop simulation diagram is shown in figure 4.1. And using from this diagram concludes the results for the various inputs and output are also verified.

Input voltage (Volts)	Output voltage (Volts)s
12	300
15	300

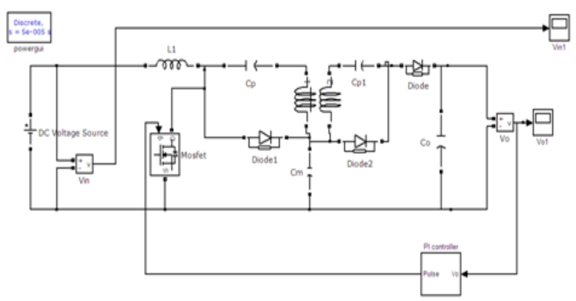


Fig. 4.1 MATLAB Simulation Diagram

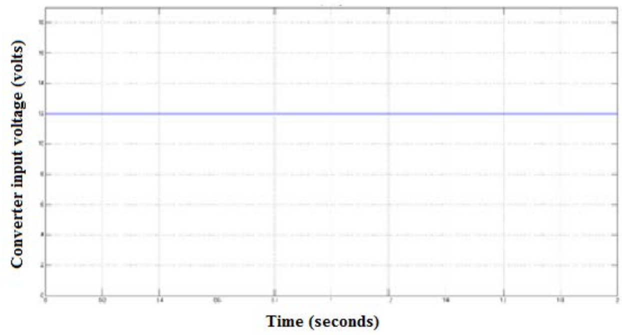


Fig. 4.2 Input Voltage for 12 V

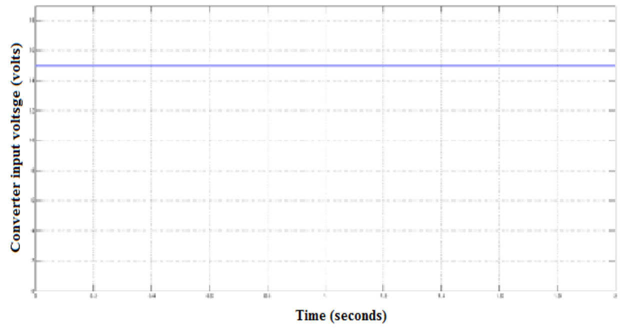


Fig. 4.3 Input Voltage for 15 V

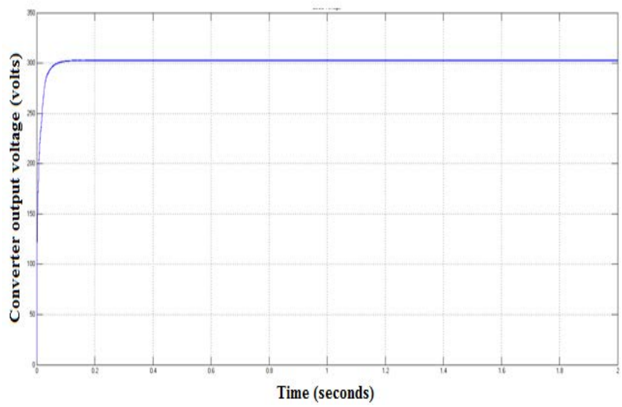


Fig. 4.4 Output Voltage for 300 V

Here the figure 4.2 and 4.3 shows the input volt is 12 volts or 15 volts. The output is maintained at 300 volts. The output is maintained constant irrespective of input voltage shown in figure 4.3. The above table shows the performance of PI controlled Modified SEPIC converter. And the input and output waveforms are shown.

V. CONCLUSION

The new topologies of non isolated high static gain converters are presented in this paper. The structure with magnetic coupling can operate with static gain higher than 20 maintaining low the switch voltage. The efficiency of proposed converter with magnetic coupling is equal to 92.2% operating with input voltage equal to 15 V, output voltage equal 300 V and output power equal 100 W. The commutation losses of the proposed converter with magnetic coupling are reduced due to the presence of the transformer leakage inductance and the secondary voltage multiplier that operates as a non dissipative clamping circuit to the output diode voltage. The simulation model is developed using MATLAB simulink for the analysis input voltage is varied. From the simulation analysis it is obvious that PI controller based Modified SEPIC converter produces constant output voltage irrespective of input voltage. It supports voltage reliability for voltage sensitive loads.

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