A Novel Low Loss, Medium Gain CI Based DC-DC Boost Converter

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***Abstract*— In metropolitan cities and smart cities pollution has been increased due to population, urbanization, and industrialization. As per the statistics of india,70% of air pollution is due to transportation. An environmentally friendly is a step toward rising living standards for future generations in promoting green transportation. One such alternative is electrified transportation, wherein governments and automotive industries should encourage usage of electric vehicles (EVs). Due to ignorance, fire incidents, storage limitations, charging times, and a lack of infrastructure still transportation is relying on engines powered by gasoline and its by-products. So, to overcome one of the limitations, a novel CI based DC-DC converter is presented in this paper. This DC-DC converter has unique, simple, and compact structure for medium gain applications. The proposed converter has few elements like coupled inductor, one controlled and two uncontrolled switches. This proposed converter is feasible for high potential converter for onboard charger, electrical drive system and fast charging infrastructure. A mathematical study was done to determine the requisite duty cycle, inductance, and capacitance values to obtain the desired gain. The CI based converter is simulated in MATLAB Simulink environment under open loop and closed loop.**

Keywords—DC-DC Converter, Coupled Inductor (CI), Electric Vehicles (EV's), Energy Storage System (ESS)

I. INTRODUCTION

Electric Vehicles (EV's) are the low running cost mode of transportation both in private and public sector in these days. Global warming, Air Pollution, Exhaustion of earth resources are major reasons to replace conventional vehicles. Soon, many auto sector companies are planning to invest in this sector for the development of passenger and goods carrier vehicles. Further, this sector is getting boost with adoption of various energy storage technologies such as hydrogen and fuel cell. The main system to be focused in the EV's are "Energy Storage System"[1-3]. The heart of ESS is energy storage devices which is the driving force of EV's. As the load varies in EV the output voltage of energy storage device also should vary, in such case energy storage devices need to be supplied with high/low current. High voltage DC generation and integration to ESS will be the major concern to drive the traction for vehicle design. So, a boost (DC-DC) power converter design is major challenge for EV's to maintain low weight, low EMI, low power loss and high reliable. Further a current controlled DC-DC converter is more practical solution for on board charger to charge ESS when it is kept for charging[4-6].

Converters design depends on their connection of elements in the circuit which are identified as non-isolated and isolated converters. Both are further sub-classified as unidirectional and bidirectional power converters. In non-isolated converters all are commonly grounded. Isolated converters are not commonly grounded, they are separated with transformers and coupled inductors. Unidirectional power converter is classified as further into single stage, multistage and multi-phase power converter. Isolated single stage DC-DC converter topologies are explored previously for buck, boost and buck-boost for various applications[7-10].
Magnetic coupling-based converters achieves the high output voltage, which can be built through transformer or coupled inductor. Converter built with transformer provides the isolation, but compared to transformer a coupled inductor is endorsed because of low leakage inductance and minimum ripple currents. So, the coupled inductor is the most prominent replacing element for a transformer. Converter built with coupled inductor will provides both isolation and non-isolation but the purpose of both will be the same, wherein it transfers energy from one to another. Coupled inductor-based converter achieves high conversion ratio and it also have few advantages like controlling the fall rate of diode current, suppressing the reverse recovery problems, and utilizing the leakage inductance etc.., [11-14].

There are various CI based DC-DC converters are available in the market [15-17]. The proposed converter has unique structure with special features. The main objective of the proposed converter is low loss, low leakage and low ripple, minimum number of elements, low duty ratio to minimize conduction losses and efficient boost converter for medium gain applications.

The proposed converter's block diagram is represented in Fig.1. The converter is mathematically analyzed and operated in section-II, Converter simulation and analysis with results of open loop is discussed in section -III, closed loop operation of proposed converter with analyzation of results are discussed in IV. Conclusion of the paper is discussed on section-V.

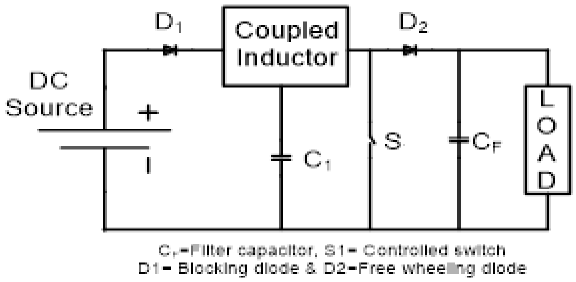

Fig.1 CI based DC-DC Boost Converter's block diagram

II. Mathematical Analysis of Proposed Converter

A. *Operation of the converter*

A novel CI based DC-DC boost converter which helps for medium power applications. Basically, the conversion ratio depends on the transformation ratio of coupled inductor, coupling factor of it and duty ratio offered on the devices. The best part of the proposed converter is medium power conversion ratio for lower duty ratio with single switch. The proposed converter contains a two-winding coupled inductor, one capacitor, single switch and one C-filter, whose schematic is presented in Fig.2.

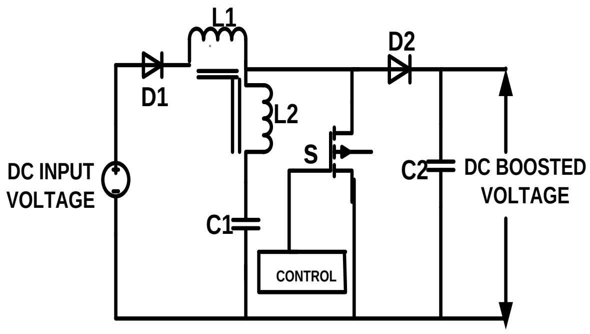

Fig.2.Schematic diagram of CI based converter under open loop

The above converter is operated in two modes, a) Switch(S) OFF state b) Switch ON state.

Mode (1) Switch(S) OFF state: Which is called as non-shoot through state, during this state, switch(S) will be in OFF state and Diode (D) will be in ON state then a Coupled Inductor and a capacitor which stores the energy as per the circuit shown in Fig.3a.The mathematical equations of non-shoot through state under steady state conditions are

$$V_{L2} = \frac{V_{in} - V_{C1}}{1-W} \quad \text{.... (1)}$$

$$V_{L1} = WV_{L2} \quad \text{.... (2)}$$

Under dynamic conditions, the capacitor(C1) is in charging state with the forward bias of diode(D1). The capacitor (C1) voltage is represented as (C1)

$$V_{c1}(t) = V_{in}(1 - cos\left(\frac{t}{\sqrt{C_1 L}}\right)) \quad \text{.... (3)}$$

The current during the charging is given by

$$i(t) = \frac{V_{in}}{\sqrt{\frac{L}{C_1}}}(1 - sin\left(\frac{t}{\sqrt{C_1 L}}\right)) \quad \text{.... (4)}$$

As long as the diode D1 is turned ON and switch S is OFF, the filter capacitor experiences a sinusoidal voltage of

$$V_{c2}(t) = V_{in}(1 - \frac{L_1}{L} cos\left(\frac{t}{\sqrt{C_1 L}}\right)) \quad \text{.... (5)}$$

Where, L is the actual inductance offered by CI and it is expressed as

$$L = L_1 + L_2 + 2M \quad \text{.... (6)}$$

Where, "k" is coefficient of coupling of CI

$$M = k\sqrt{L_1 + L_2} \quad \text{.... (7)}$$

Mode (2) Switch(S) ON state: which is called as shoot through state, in this state switch(S) will be ON and Diode will become OFF state because the potential at switch will be higher compared to input voltage. It is observed that capacitor charged voltage is twice of the input voltage when the diode is turned off as per the circuit shown in Fig.3b. The mathematical equations of shoot through state under steady state conditions are

$$V_{L2} = V_{C1} \quad \text{.... (8)}$$

Under dynamic conditions, when the switch S is turned ON, i.e., during T_{ON}, the filter capacitor C_2 provides the required voltage to the load while the coupled inductor and capacitor are discharging. It is observed from eq. (3), the maximum capacitor voltage can be double the input voltage V_{in} provided. The capacitor voltage is discharges through switch (S) because of diode(D1) get reverse biased. The diode D_2 prevents the filter capacitor C_2 from discharging during $T_{\bar{O}N}$.

$$V_o(t) = V_{in}(1 - \frac{L_1}{L} cos\left(\frac{t}{\sqrt{C_1 L}}\right)) \quad \text{.... (9)}$$

B. *Design Specifications*

The inductors L_1 and L_2 are coupled using a ferro magnetic core with coefficient of coupling close to 1. Hence, these both inductors together called as a coupled inductor. The polarity of winding is done in such a way that the mutual inductance produced adds up to the actual inductance. The first coil inductance (L1) is 3µH and second coil inductance (L2) is 6µH with coefficient of coupling (k) is 0.99 and mutual inductance in the coupled inductor is 4.2e-4H. Applied voltage to the converter as (Vin) 5volts, Capacitor connected in the converter(C1) is 470µF, Filter Capacitor(C2) is 470µF, Load resistance(R) is 200Ω.

III. Simulation of Proposed Converter under Open Loop Condition

The proposed converter is designed and simulated in MATLAB Simulink environment under open loop is shown in Fig.4.Simulation of the circuit is applied with voltage (Vin) of 5volts and duty ratio of 10% observed the boosted output voltages with variable load resistance as presented in Fig.5.The effect of output voltages with load variations are tabulated in Table.1. The MATLAB/SIMULINK circuit with the applied voltage (Vin) of 5volts @200ohm's of load with different duty ratios are represented and tabulated in Fig.6. and inTable.2.

From the results and tables, it is observed that the converter has gain sensitivity i.e., with the change of load or change of duty ratio the output voltage is varying. Finally, the gain the converter is changing accordingly. So, in order to make the system stable, the converter need to operate in closed loop condition.

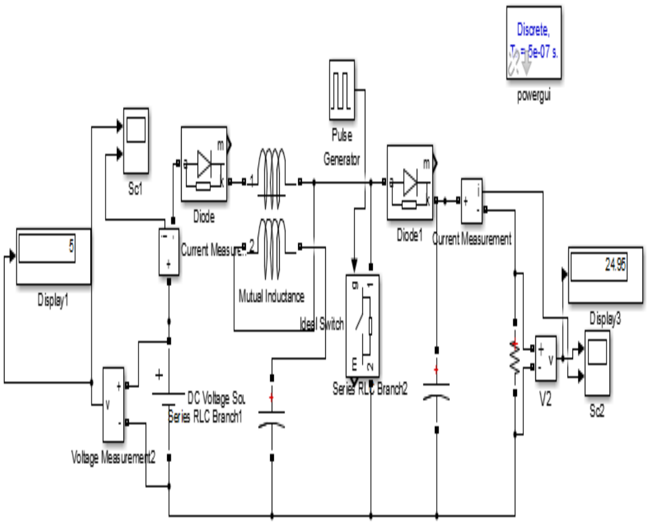

Fig.4. MATLAB/SIMULINK circuit of converter (DC-DC) under open loop

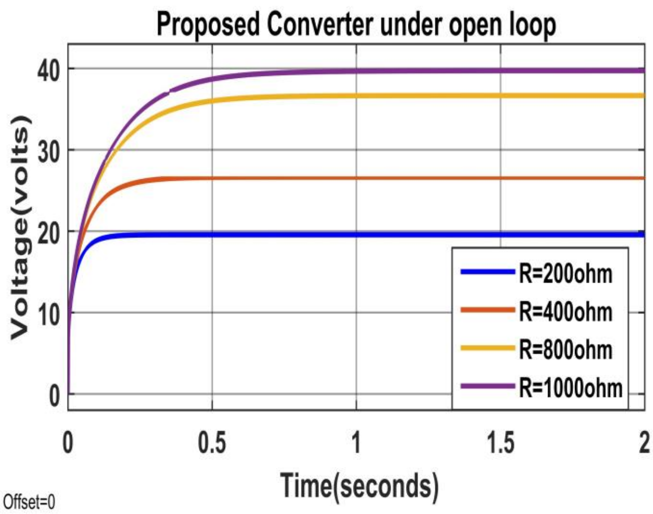

Fig.5 Output Voltages of converter with variable load resistance @Vin=5volts, D=10%

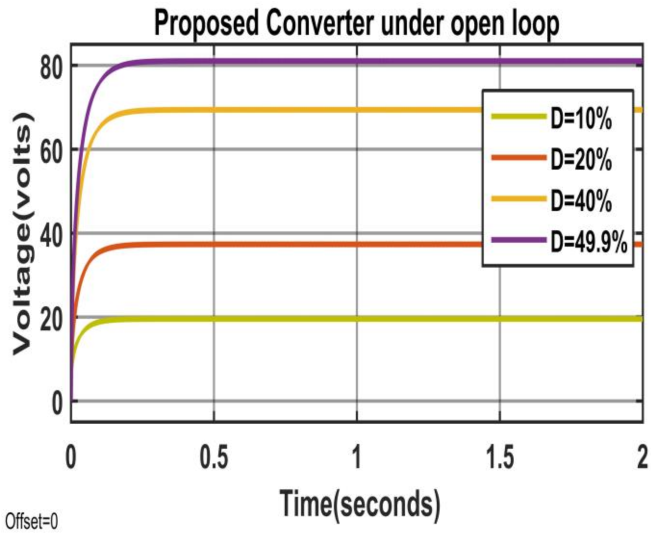

Fig.6. Output Voltages of converter with different duty ratio @Vin=5volts,R=200Ω

TABLE 1. OUTPUT VOLTAGES WITH DIFFERENT LOADS

S.No.	***Duty Ratio @ 10%***	
	Load (R) in Ω	***Output Voltages (Vo) in Volts (simulation)***
1	100	14.45
2	200	19.55
3	300	23.55
4	400	26.63
5	500	29.86
6	600	32.54
7	700	34.76
8	800	36.64
9	900	38.24
10	1000	39.6

TABLE 2. OUTPUT VOLTAGES WITH DUTY RATIO VARIATION @200Ω LOAD RESISTANCE

S.No.	***Constant Load Resistance @200Ω***	
	Duty Ratio (D) in %	***Output Voltages (Vo) in Volts (simulation)***
1	10	19.55
2	20	37.34
3	30	54.26
4	40	69.4
5	49.9	81.03

IV. Simulation of Proposed Converter Under Closed Loop Condition

The gain sensitivity problem raised in open loop is overcome with the design of controller. A controller of PI is designed as Proportional with 1 and Integral with 15 with the tuning method in MATLAB Simulink. The proposed converter is operated under closed loop with PI controller. The diagram of converter under closed loop control is available in Fig.7.

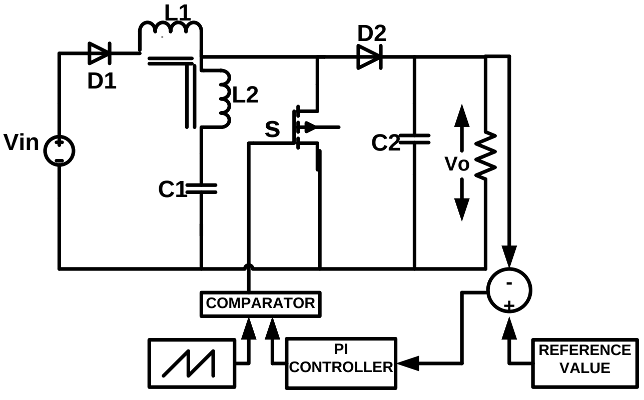

Fig.7 Circuit diagram of Converter under closed loop control

The MATLAB/SIMULINK circuit of converter under closed loop control is simulated in Fig.8. Under closed loop PI controller, the converter is set with a reference of 70 as indicated in Fig.8.The output voltages are said to be constant under different loads are represented and tabulated in Fig. 9. And Table.3 @ input voltage (Vin) of 5volts.Similarly the output voltages are constant with different input voltages @ load resistance of 200Ω as projected in Fig.10 as tabulated in Table.4.

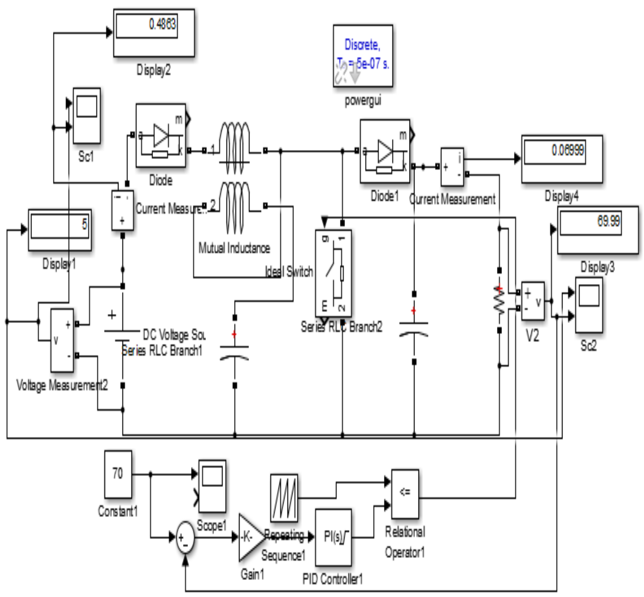

Fig.8. MATLAB/SIMULINK circuit of converter (DC-DC) under closed loop contol

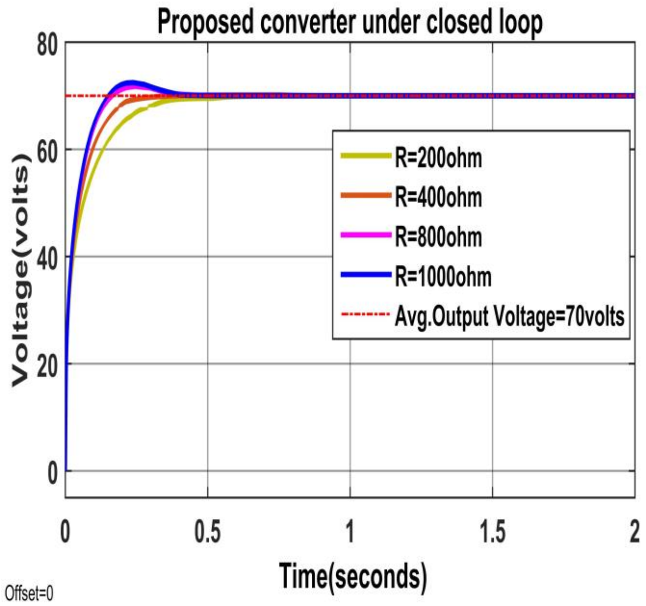

Fig.9. Output Voltages of the converter with different loads @Vin=5volts

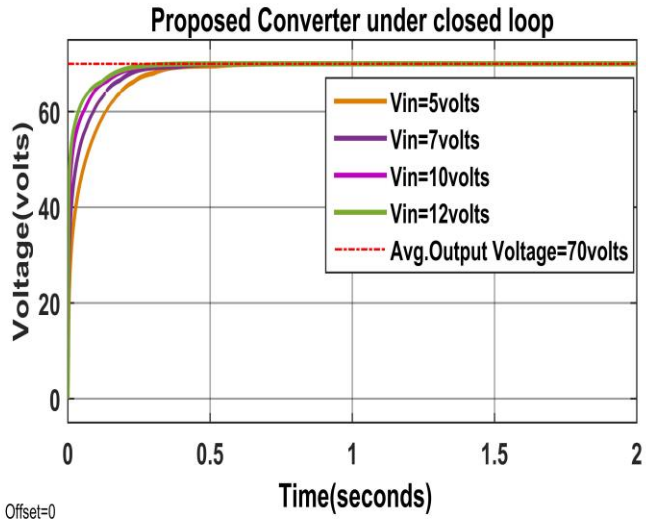

Fig.10. Output Voltages of the converter with differnt input voltages @load of 200Ω

TABLE 3. OUTPUT VOLTAGES WITH CHANGE IN LOAD RESISTANCE

S.No.	*Input Voltage @ 5 volts*	
	Load (R) in Ω	***Output Voltages (Vo) in Volts (simulation)***
1	100	69.95
2	200	69.98
3	300	69.98
4	400	69.99
5	500	69.99
6	600	69.99
7	700	70.00
8	800	70.00
9	900	70.01
10	1000	70.01

TABLE 4. OUTPUT VOLTAGES WITH DIFFERENT INPUT VOLTAGES

S.No.	*Load Resistance @200Ω*	
	Input voltage (Vin)	*Output Voltages (Vo) in Volts (simulation)*
1	5	69.98
2	7	69.97
3	10	69.97
4	12	69.97

V. CONCLUSION

A novel CI based boost converter is designed for medium gain applications. The novel converter is analyzed with mathematical approach and it is simulated in MATLAB Simulink under open loop control. From the results, we observed that the converter has the problem of gain sensitivity i.e., the output voltage of converter got effected with change in load and as change in duty ratio. The above said issue was solved by designing a controller. A PI controller is designed for the proposed converter operated as closed loop. From the results it was observed that the variation of load or variation of input voltage will not affect the output voltage, it will set to reference value which is constant. Finally, the proposed converter is suitable for medium power generation which can ne used in electric vehicles.

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