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ANALYSIS OF SOLAR INTEGRATED SYMMETRICAL HYBRID SWITCHED-INDUCTOR DC-DC CONVERTER FED SRM DRIVE FOR ELECTRIC VEHICLE APPLICATION

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Abstract

In profound applications like photovoltaic systems, smart lighting systems and automobile sector, high gain DC-DC converters are pioneered to step-up the low voltage level to high voltage. Classical Boost converter is limited with its voltage gain owing to the efficiency of the system and current ripples. This paper presents a genre of Symmetrical Hybrid Switched Inductor Boost converter powered from a solar photovoltaic system for high step-up voltage conversion ratio. The topological root of the Symmetrical Hybrid Switched Inductor Boost converter is from the combination of active and passive units. The converter is analyzed, compared with existing topologies and details are presented. The Symmetrical Hybrid Switched Inductor Boost converter output is connected to Switched Reluctance Motor to drive the wheels of an electric vehicle. The coils of 6/4 SRM is fed from Asymmetrical converter. The proposed system is analyzed and results are shown using MATLAB/SIMULINK software.

Index Terms: Symmetrical Hybrid Switched Inductor Boost converter, Electric Vehicle, Photo-Voltaic (PV), DC-DC Converters, Switched reluctance motor (SRM), motor drive.

1. INTRODUCTION

Energy from photovoltaic (PV) system has gained interest in recent years and is capable of solving the energy crisis. Solar PV system is one of the prominent part of renewable resources. Energy from PV system has become most reliable source because of its free and infinite power. Many advantages including zero pollution, production cost, availability and life-span [1-2]. One main concern of PV system is its low output voltage and in many electrical applications, this low voltage is not sufficient to drive the load. To avoid this nature of PV system, either PV modules are to be connected in series or to use DC-DC converters to meet the load requirements.

Traditional step-up converters give high voltage gain by increasing duty cycle but at the loss of efficiency with high current ripples. Many DC-DC converter topologies have been developed to give high voltage gain with slight duty cycle. Isolated DC-DC converters increase the turns ratio to give out high gain [3-7]. Isolated converters, extracted from Buck Converter, and reflect high input current ripple and high voltage stress across output diode. Isolated converters, extracted from Boost Converter, reflects voltage spike across switch which generated from leakage inductance [8-10]. Non-Isolated DC-DC converters yields high voltage ratio with good efficiency. Coupled inductor type Isolated DC-DC can give out high voltage gain by increasing the turns ratio [11-16]. The leakage inductance is unavoidable in Coupled inductor type Isolated type of converters and can cause high spike

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in voltage, stressing the switch during turn-off [17-18]. Non-coupled inductor type Isolated type of converters can yield high gain with less magnetic components [19-22].

Different topologies pertaining to switched-inductor and switched-capacitor with extended range of voltage gain are furnished in [23-28]. With the adaption of series and parallel switched-inductor cells, high voltage gain ration can be achieved. This paper presents a genre of Symmetrical Hybrid Switched Inductor Boost (SH-SL) converter [28-29] with the combination of active and passive units. SH-SL converter is powered from a solar PV system. Freely available energy like solar-PV systems [30-33] can drive the traction motor [34] of electric vehicle (EV). EVs run by emitting zero air pollution and can replace the polluting scenario with conventional vehicles. Ferrite materials with high magnetic permeability and low coercive motors have gained importance these days, replacing permanent magnet machines. Switched reluctance motor (SRM), which is capable of running at high speeds [35-36] with simple construction, is suitable to drive EV.

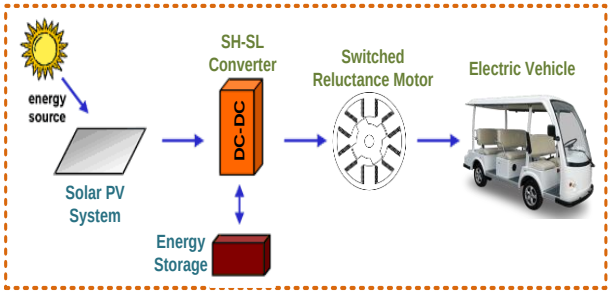

Fig. 1. Block diagram of the system

This paper presents a genre of Symmetrical Hybrid Switched Inductor Boost converter powered from a solar photovoltaic system for high step-up voltage conversion ratio. The topological root of the Symmetrical Hybrid Switched Inductor Boost converter is from the combination of active and passive units. The converter is analyzed, compared with existing topologies and details are presented.

The Symmetrical Hybrid Switched Inductor Boost converter output is connected to Switched Reluctance Motor to drive the wheels of an electric vehicle. The block diagram of the system is shown in figure 1.

I. Symmetrical Hybrid Switched Inductor Boost Converter

A. Symmetrical Hybrid Switched Inductor Boost Convertre Representation

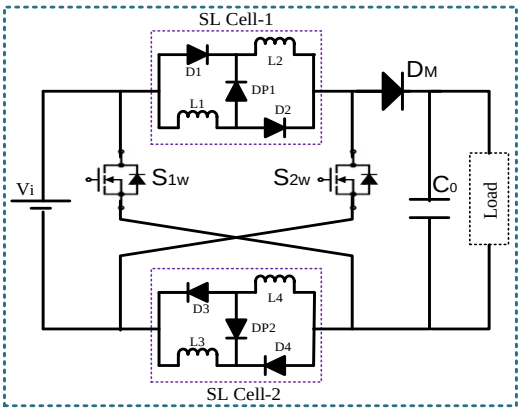

Fig.2. SH-SL Boost converter

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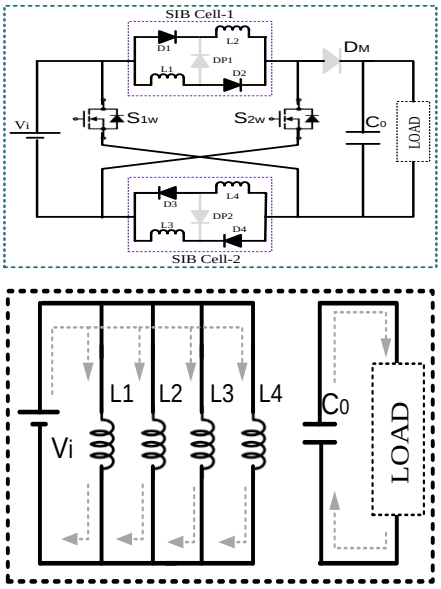

Fig. 3. SH-SL converter in Mode-1

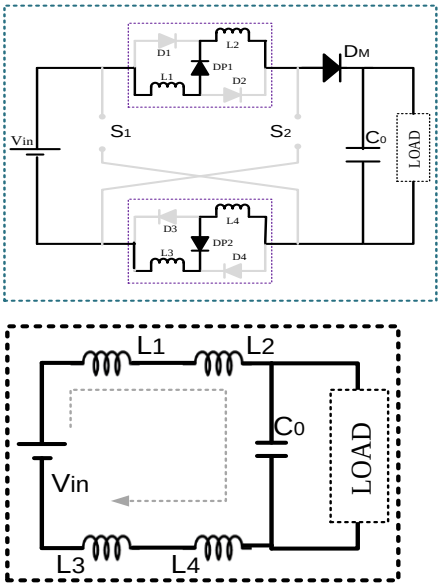

Fig. 4.SH-SL converter in Mode-2

Figure 2 shows the schematic circuit of symmetrical Hybrid Switched Inductor (SH-SL) Boost converter. SH-SL converter is formed by combining active and passive switched-inductor (SL) units. Such units are shown as SL cell-1 and SL cell-2 in Figure 2. Each SL cell consists of two inductors and three diodes. SH-SL converter consists of two power switches S1w and S2w, generally MOSFETs, and output capacitor.

High gain is achieved by clamping active and passive units. The inductors, by turning ON two power switches, form an active SL unit (mode-1 of operation). The SL cell with three diodes and two inductors with two power switches turned OFF forms passive SL unit (mode-2 of operation). The modes of operation of SH-SL converter under continuous conduction mode (CCM) are explained below and the analysis is carried out considering equal inductance values. SH-SL Converter Modes in CCM Operation

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Mode-1: Both the switches S1w and S2w are turned ON. The elements form an active SL unit and the input voltage presents across inductors. Inductors L1 to L4 shapes to parallel and are imposed to input voltage level. Capacitor discharges and acts as source to the load. The current flow path and the equivalent circuit are shown in Figure 3. The voltage across inductor is expressed as:

$$Vi = V_{L1}=V_{L2}=V_{L3}=V_{L4} \quad (1)$$

Mode-2: Both switches S1w and S2w are OFF. The elements form a passive SL unit and the four inductors L1, L2, L3 and L4 are discharged to the output forming a series circuit. The current flow path and the equivalent circuit is shown in figure 4. Voltage across the inductor (L1=L2=L3=L4) is given by (2).

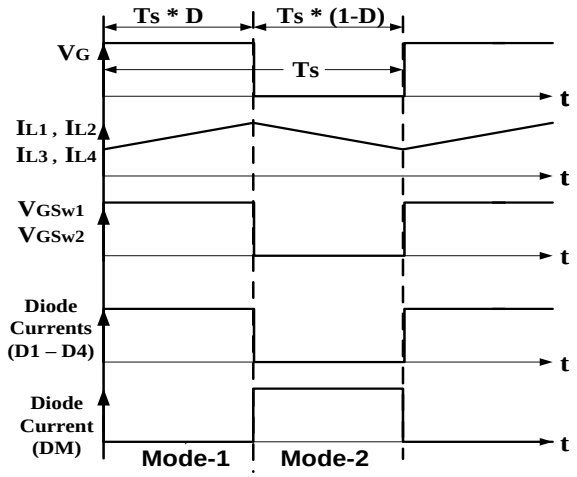

Fig.5. Continuous Mode device characteristics of SH-SL converter

$$V_L = \left(\frac{V_{in}-V_0}{4}\right) \quad (2)$$

The operational timing diagram of is detailed in Figure 5 for SH-SL converter in CCM operation. The gain of hybrid boost converter using equations (1) and (2) is:

$$\frac{V_{in}*DT_s+\left(\frac{V_{in}-V_0}{4}\right)(1-D)T_s}{T_s} = 0 \quad (3)$$

$$V_{gain} = \frac{V_0}{V_{in}} = \frac{1+3D}{1-D} \quad (4)$$

Duty cycle formulation, equation (4) is modified as

$$(1-D)*V_0 = (1+3D)*V_{in}$$

$$D = \frac{V_0-V_{in}}{V_0+3V_{in}} \quad (5)$$

$$\frac{V_{in}*DT_s+\left(\frac{V_{in}-V_0}{2}\right)(1-D)T_s}{T_s} = 0 \quad (6)$$

$$V_{gain} = \frac{V_0}{V_{in}} = \frac{1+D}{1-D} \quad (7)$$

Furthermore, equation (7) is modified as

$$(1-D)*V_0 = (1+D)*V_{in}$$

$$D = \frac{V_0-V_{in}}{V_0+V_{in}} \quad (8)$$

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B. Analysis of SH-SL Converter

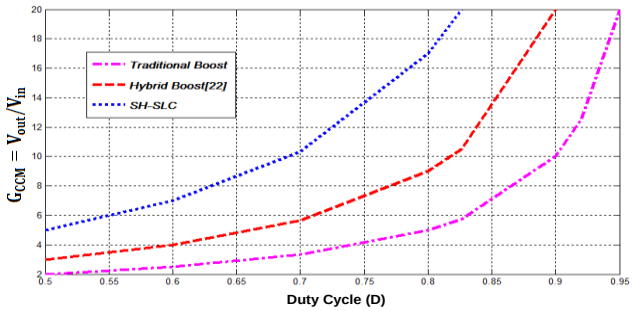

Fig.6. Duty cycle versus voltage gain comparison

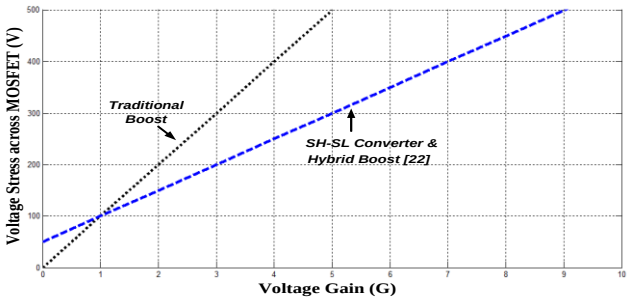

Fig.7. Voltage stress comparison

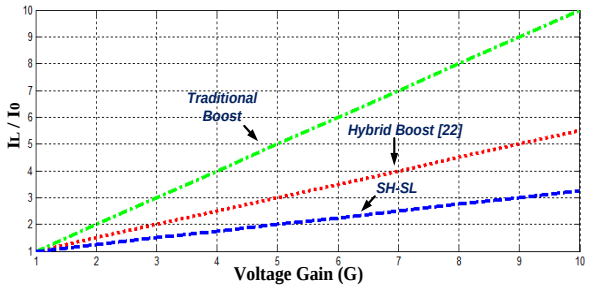

Fig. 7. Inductor current comparison

With different inductor values in SH-SL converter, the voltage stress across switch increases and thus analysis with equal inductance is considered. With equal inductor topology, the inductors can be integrated with single core which lessens the size of magnetic components. The gain in voltage is shown in figure 5. Gain is high and high output voltage is obtained with less duty cycle which eventually reduces the current ripple and current stress on the components. Voltage stress across the main switch is less compared to existing topology as shown in figure 6 and efficiency increases with less cost. Figure 7 shows the average inductor current and the amount of current through inductor is less.

C. Design of SH-SL Converter

SH-SL converter is designed to operate with 100V input and 500V output. The operating frequency of the converter is considered to be 10 KHz and power rated at 1KW.
Duty Cycle of converter for 100V input and 500V output voltage values, the duty cycle (D) is calculated as 50%.

Inductance L=10 mH

Capacitance C=10μF

Table-1 illustrates parametric design of Hybrid Boost converter. Table-2 shows the comparative illustration of SH-SL converter with existing converters.

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TABLE I: HYBRID BOOST CONVERTER PARAMETERS

Parameter	Value
Input source Voltage, V_{in}	100V
Output Voltage, V_0	500V
Power, P	1 KW
Switching Frequency, F_S	10KHz
Inductor Current ripple, ΔI_L	0.5 A
Capacitor Voltage ripple, ΔV_C	10 V
Inductor, L	10 mH
Capacitor, C	10 µF

TABLE II: COMPARATIVE CHART

Parameter	Traditional Boost	Hybrid Boost [22]	SH-SL
Voltage Gain	$\frac{1}{1-D}$	$\frac{1+D}{1-D}$	$\frac{1+3D}{1-D}$
Number of Diodes	1	1	7
Number of MOSFETs	1	2	2
Voltage across MOSFET	GV_{in}	$\frac{(G+1)V_{in}}{2}$	$\frac{(G+1)V_{in}}{2}$
Voltage across Output Diode	GV_{in}	$(G+1)V_{in}$	$(G+1)V_{in}$
Current through Inductor (I_L)	GI_0	$\frac{(G+1)I_0}{2}$	$\frac{(G+3)I_0}{4}$

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II. PV WITH SH-SL CONVERTER FED SRM DRIVE

A. PV System with SH-SL Converter

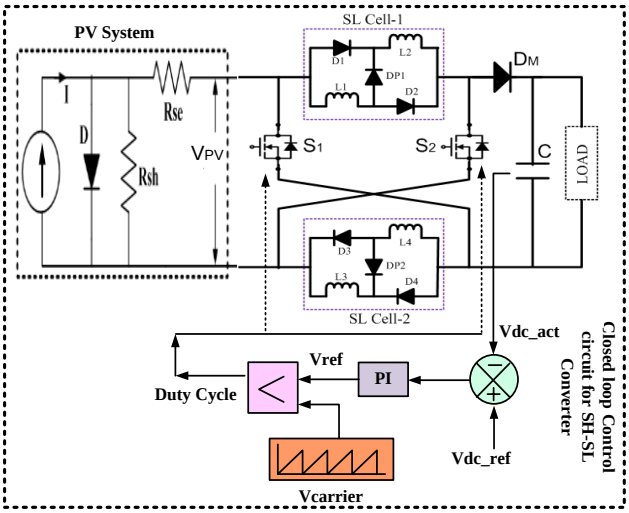

Fig 8. PV with SH-SL converter

PV system doesn't give out voltage level which is suitable to drive any load. PV system insists for DC-DC boost converter to increase its voltage level at user point. Figure 8 illustrates PV system with SH-SL converter. The output of the PV system is connected to SH-SL converter and the load parameters of the SH-SL converter are fed back to controller to generate gate pulses to switches of the converter. With this loop operation, desired output of DC-DC converter can be achieved.

B. SRM with Asymmetrical Converter

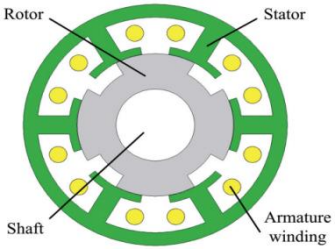

Fig. 9. Three-Phase 6/4 SRM

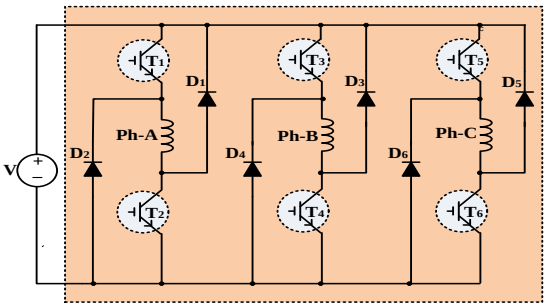

Fig.10. Conventional asymmetrical structure converter for SRM

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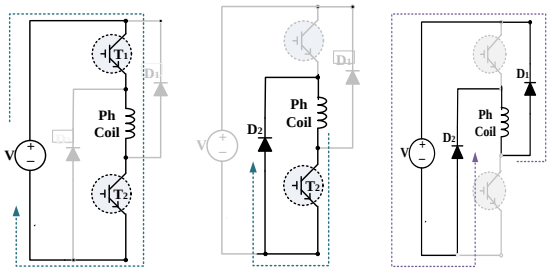

(a) Excitation (b) Free-wheeling (c) Regeneration

Fig. 11. Operating modes of SRM

Constructional view of SRM is shown in figure 9 and the converter exciting the phases of SRM is shown in figure 10. The three modes – excitation, free-wheeling and regeneration are represented in figure 11. Robust and simple construction makes SRM suitable for many applications. Its high speed capability suits for EV. By sequentially switching (as in figure 11) the power switches in asymmetrical converter, SRM can be operated in three modes.

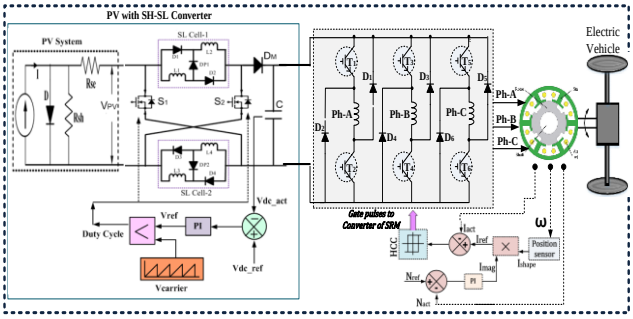

Fig. 12. Solar with Hybrid Boost Converter and SR Motor Drive

C. PV with SH-SL Converter with Switched Reluctance Motor Drive for Electric Vehicle application

Photo-voltaic system with SH-SL converter to feed the SRM for EV application is shown in figure 12. The output of the PV system is given as an input to the SH-SL converter which increases the voltage level. The output of the converter is fed to asymmetrical converter to excite the stator coils of SRM to generate flux to align the rotor. SRM drive is in feedback mode where the respective control operation takes place and speed is adjusted according to the desired value.

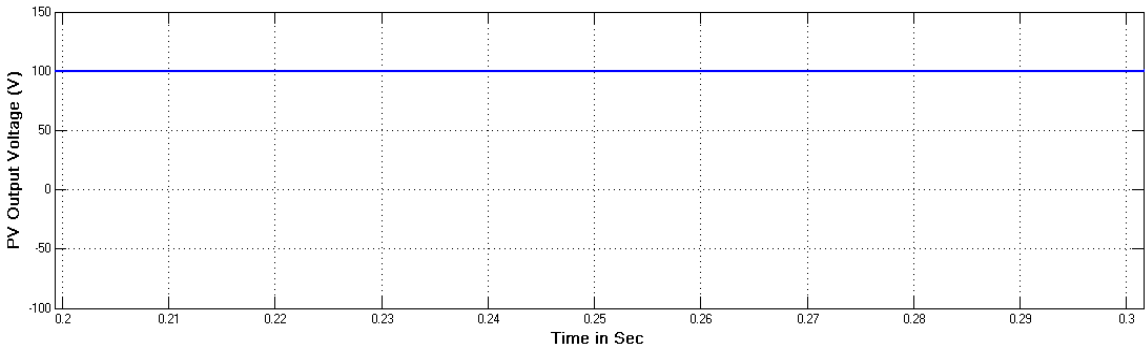

Fig. 13. PV output voltage

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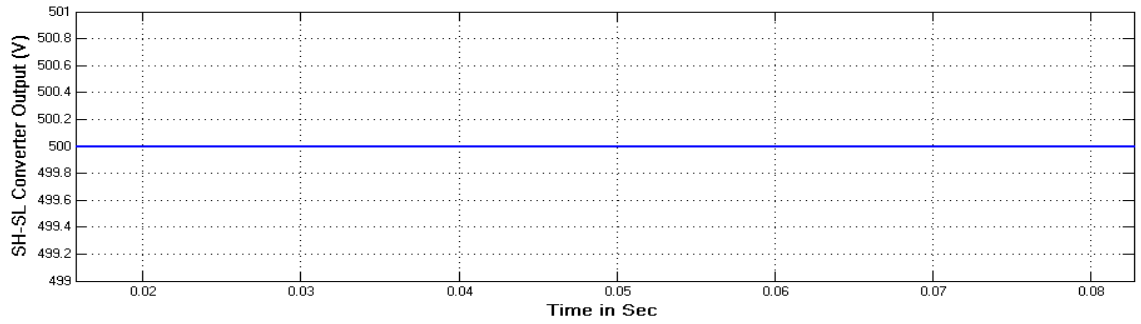

Fig. 14. Output voltage of Hybrid converter

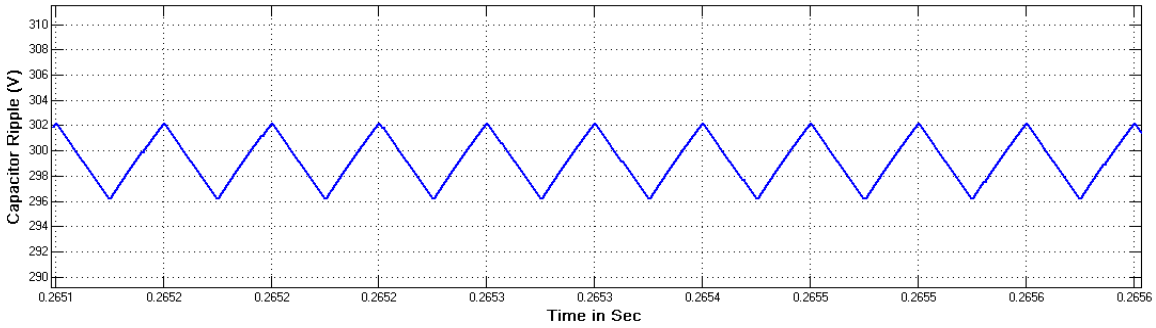

Fig. 15. Change in inductor current

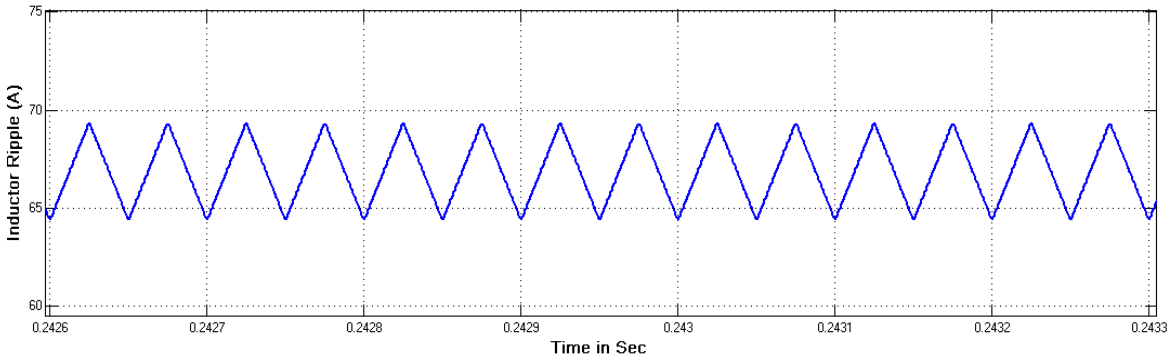

Fig. 16. Change in Capacitor voltage

III. RESULT ANALYSIS

A. PV with SH-SLC and SRM with fixed torque and speed

The voltage wave shape at the output of solar system is shown in figure 13. The PV system yields a voltage of 100V. This output of PV system will be the source to SH-SL converter. SH-SL converter is designed to give five times the output voltage. The output of PV system is increased by five times to 500V as in figure 14. Inductor ripple current and the capacitor ripple voltage are shown in figure 15 and figure 16 respectively.

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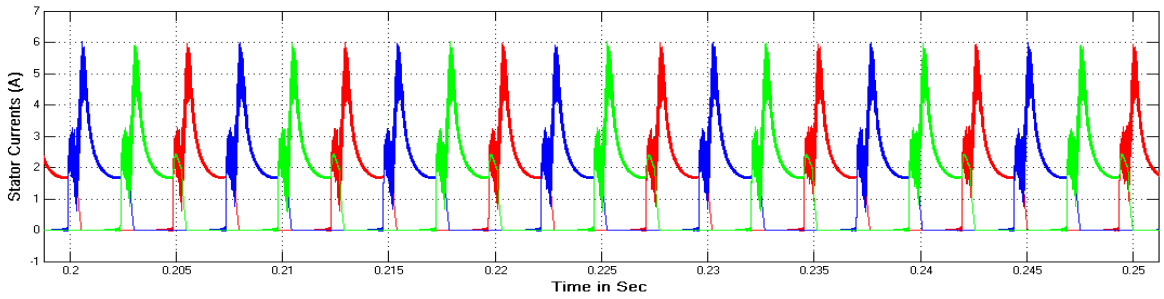

Fig. 17. SRM stator excitation currents

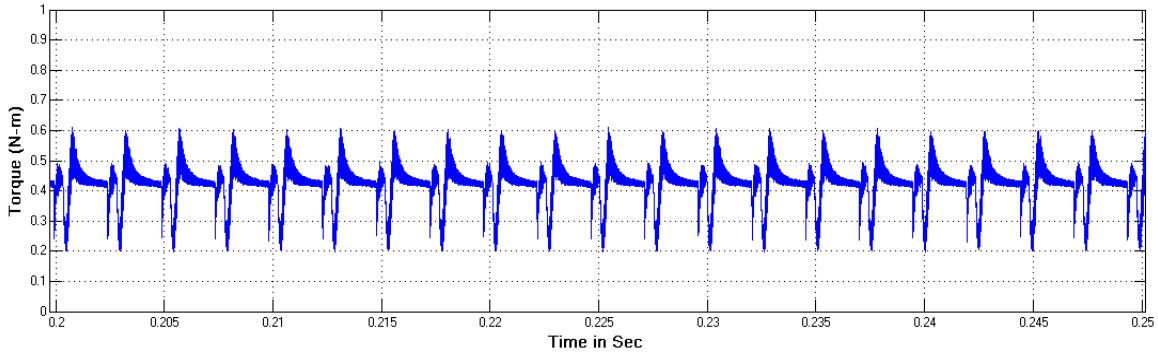

Fig. 18. SRM torque characteristics

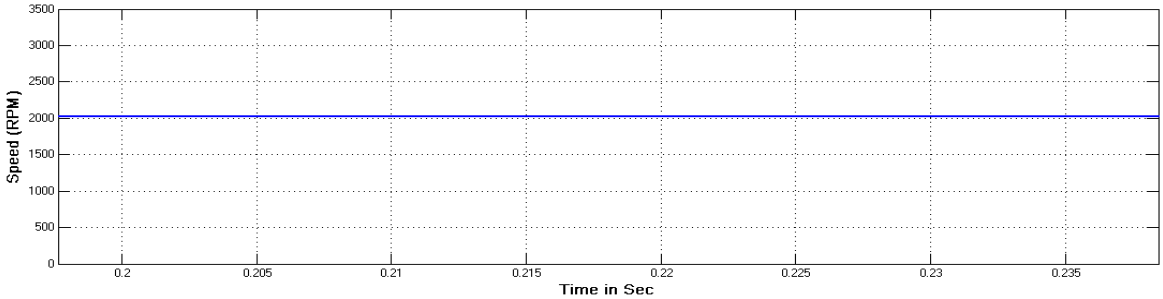

Fig. 19. SRM rotor running speed

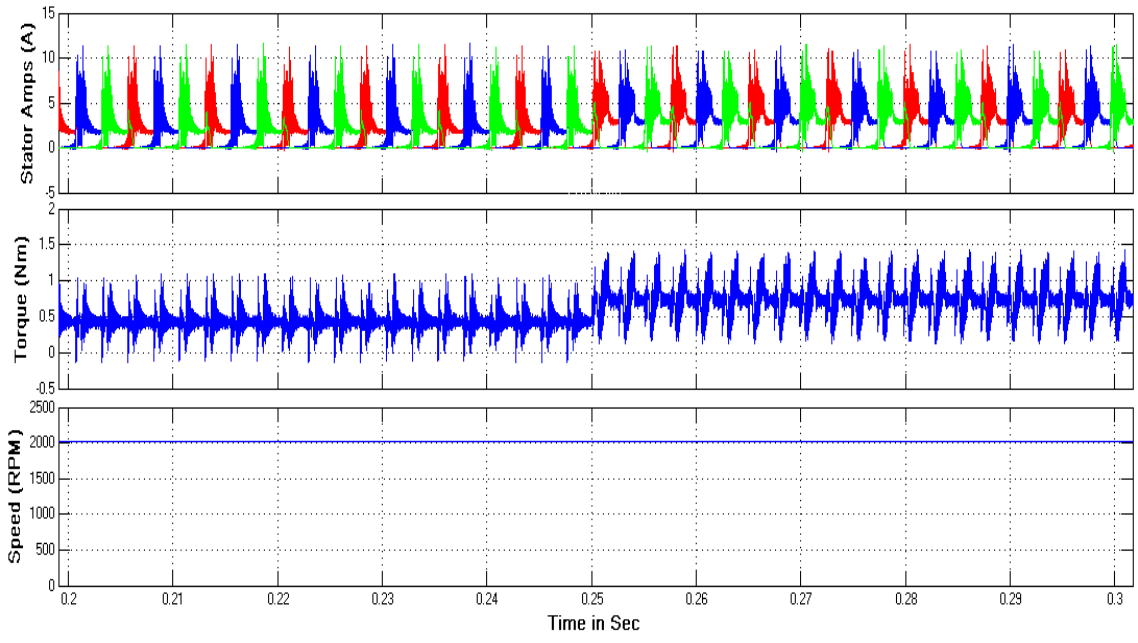

Fig. 20. Stator currents, Torque and speed of SRM drive

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Switched Reluctance Motor characteristics to drive an electric vehicle are shown in figures 17, 18 and 19. The stator currents, torque and speed curves are shown respectively. The rotor speed is constant at 2000rpm when the stator is excited with 6A current.

B. PV with SH-SLC and SRM with varied torque and fixed speed

PV and SH-SL converter output remains same as shown in case-1. Switched Reluctance Motor characteristics to drive an electric vehicle are shown in figure 20. The stator currents, torque and speed curves are shown respectively. The rotor speed is constant at 2000rpm when the stator is excited. The rotor speed is constant at 2000rpm when the stator is excited and with variable torque condition. Though the torque is changed at 0.25 sec, the speed does not vary.

IV. Conclusion

During last few years, there is a constant effort from the field of power electronics to meet the challenges while using renewable energy sources. Electric vehicles are latest trends to replace traditional IC engine transport which pollutes the environment. This article demonstrates the solar-PV with symmetrical hybrid – switched inductor boost converter and traction switched reluctance motor. The gain of SH-SL DC-DC converter is better compared to other converter topologies. The SH-SL DC-DC converter is analyzed, compared with existing topologies and details are presented. SH-SL DC-DC is run in closed-loop operating mode, and closed-loop speed control is adopted for SRM drive. Design of SH-SL DC-DC is discussed in the article. Switched reluctance traction motor stator coils are excited from asymmetrical converter. SRM drive running with fixed speed applied with fixed torque and variable torque is analyzed for drive train application.

Conflict of Interest

"The authors declare no conflict of interest".

Author Contributions

Ravi Kiran Dasari conducted the research; analyzed the data; wrote the paper. Dr. Godwin Immanuel supervised the work; all authors had approved the final version.

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