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Design and Analysis of Boost, Interleaved Boost and Hybrid Boost Converters for PMSM Drive with Closed-Loop Speed Control

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Abstract: Cutting-edge technology in power engineering led to the development of power electronic converter fed motors. Motors are developed employing rare earth materials called permanent magnet synchronous motor (PMSM) which are driven from power electronic converter. Photo-voltaic (PV) system is the source feeding the converter for PMSM drive in this paper. PV output voltage is gained using a voltage booster circuit. This paper explains the design and analysis of conventional boost converter; interleaved boost converter and Hybrid boost converter voltage booster circuits to drive PMSM. PMSM drive is operated in closed-loop mode and controlled with PI controller. PV fed Closed-loop PMSM drive with boost converter; interleaved boost converter and Hybrid boost converter are validated with fixed and variable speed conditions. Simulation models are developed and results are presented using MATLAB/SIMULINK software.

Keywords: PMSM, Boost converter, interleaved boost converter, hybrid boost converter, speed control, closed loop.

1. INTRODUCTION

With the wide requirement of high-performance motors in many instances of daily applications, permanent magnet synchronous motors (PMSM) [1-3] are trending in electrical engineering. Development of electrical motors manufacturing using rare earth materials (as permanent magnets) rather to place windings for the generation of magnetic field like permanent magnet synchronous motors (PMSM) came into existence. PMSM is capable of rotating with high speeds [4]. PMSM machines are small in size and weights less. PMSM machines are designed to have exceptional dynamic response and have soaring power density making them further appropriate for high speed applications.

Permanent magnet synchronous motor (PMSM) is a synchronous machine in which required magnetic field is generated from rotating permanent magnets (rotor). Permanent magnet synchronous motor has sinusoidal shape back EMF [5-7]. PMSM machines are controlled from a power electronic converter which resembles an inverter where the supply input is DC power and output fed to motor stator windings is AC power. DC power input is fed from photo-voltaic (PV) system. The non-conventional source of energy PV system [8-9] transforms photon energy available in the sunlight in to electrical energy. The photo-voltaic cell absorbs the photons and depletes the depletion layer allowing electrons to flow producing electrical current. The generated electricity is DC power with low voltage rating.

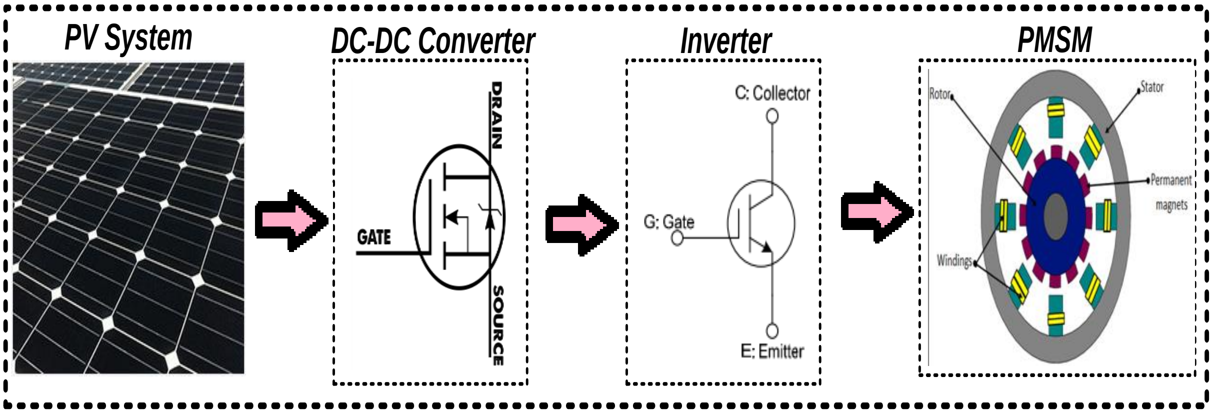

Figure 1: Block Diagram of PV fed PMSM with DC-DC converter

The generated low voltage electricity from PV system insists for a DC-DC converter to step-up the voltage rating. Power electronic technology developed many DC-DC converters. Input and output signals of DC-DC converter [10] are DC type. Output voltage of a DC-DC converter can be at higher or lower level with reference to input. DC-DC converters are classified as isolated and non-isolated type. Isolated type DC-DC converters consist of transformer to isolate the input terminal and output terminal. In non-isolated type, absence of transformer connects the input and output terminals of the converter.

Figure 1 illustrates the basic block Diagram of PV fed PMSM with DC-DC converter. Conventional boost converter suffers from having poor efficiency with high duty cycle. Efficiency of boost converter can be increased by breaking up the output current path in to two which cuts down the inductor losses and I^2R losses giving out interleaved structure. Interleaved Boost converter gives reduced ripple content in current. Further hybrid boost converter is analyzed in this paper.

This paper explains the design and analysis of non-isolated type DC-DC converters. Conventional boost converter, interleaved boost converter and Hybrid boost converter voltage booster circuits to drive closed-loop PMSM are analyzed in this paper. PMSM drive is controlled with PI controller and PV system is the source to Closed-loop PMSM drive with boost converter; interleaved boost converter and Hybrid boost converter.

2. CLOSED-LOOP PV WITH BOOST CONVERTER FED PMSM

2.1 Boost converter

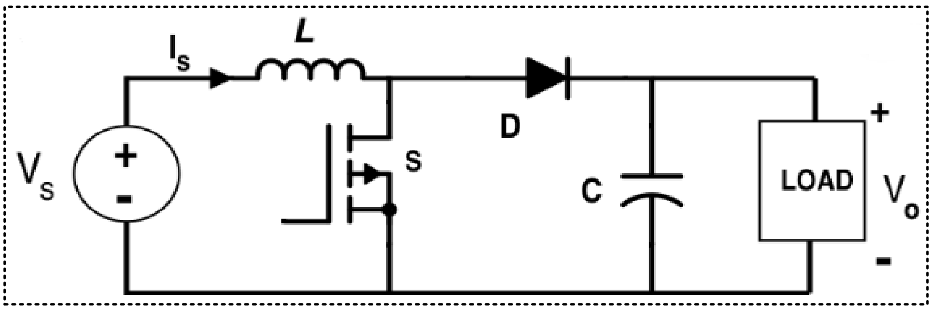

Figure 2: Conventional Boost converter

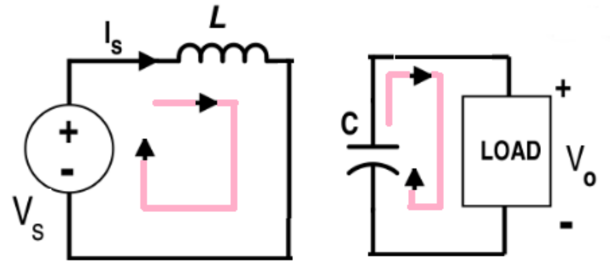

Fig 3: Boost converter when switch is ON

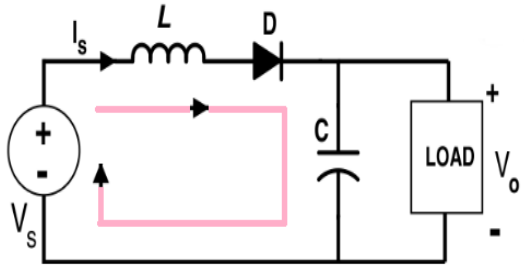

Fig 4: Boost converter when switch is OFF

Boost converter is the basic form of DC-DC converter used widely to gain the voltage level of the system. The basic circuit of boost converter is represented in figure 2. Basic boost circuit consists of a voltage source, an inductor, high frequency switch, a diode and a capacitor. The operation of the boost converter is explained by turning ON and OFF the switch. The circuit look alike of boost converter when switch is ON and switch is OFF is shown in figure 3 and figure 4 respectively.

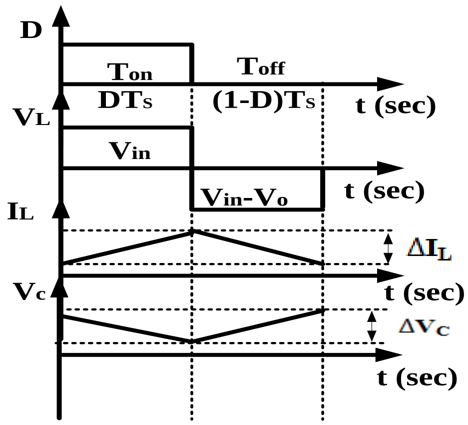

Figure 5: Timing diagram of boost converter.

When the switch is ON, the current from the source charges the inductor and completes the circuit through short circuited switch and back to source. The diode is reverse biased and switch ON condition isolates the source terminal and the load terminal. In this case, the capacitor drives the load. The inductor is charged up to the voltage level equal to source value. The voltage across inductor is equal to source voltage ($V_{in}=V_s$) and equation can be written as (1).

$$\frac{dI_L}{dt} = \frac{V_{in}}{L} \tag{1}$$

When the switch is OFF, the charged inductor (voltage level equal to source value) forcefully forward biases the diode and current from the source through charged inductor charges the capacitor. The output voltage across the load (capacitor) depends on the duty cycle of the circuit. Voltage across inductor can be written as equation (2).

$$\frac{dI_L}{dt} = \frac{V_{in} - V_{out}}{L} \tag{2}$$

The timing diagram of boost converter is defined in figure 5. Making average voltage of the inductor zero can yield the voltage gain formulation (equation (4)) for boost converter.

$$V_L = D * V_{in} + (1 - D) * (V_{in} - V_{out}) = 0 \quad (3)$$

$$\text{Voltage gain} = \frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (4)$$

2.2 PV with boost converter fed closed-loop PMSM drive

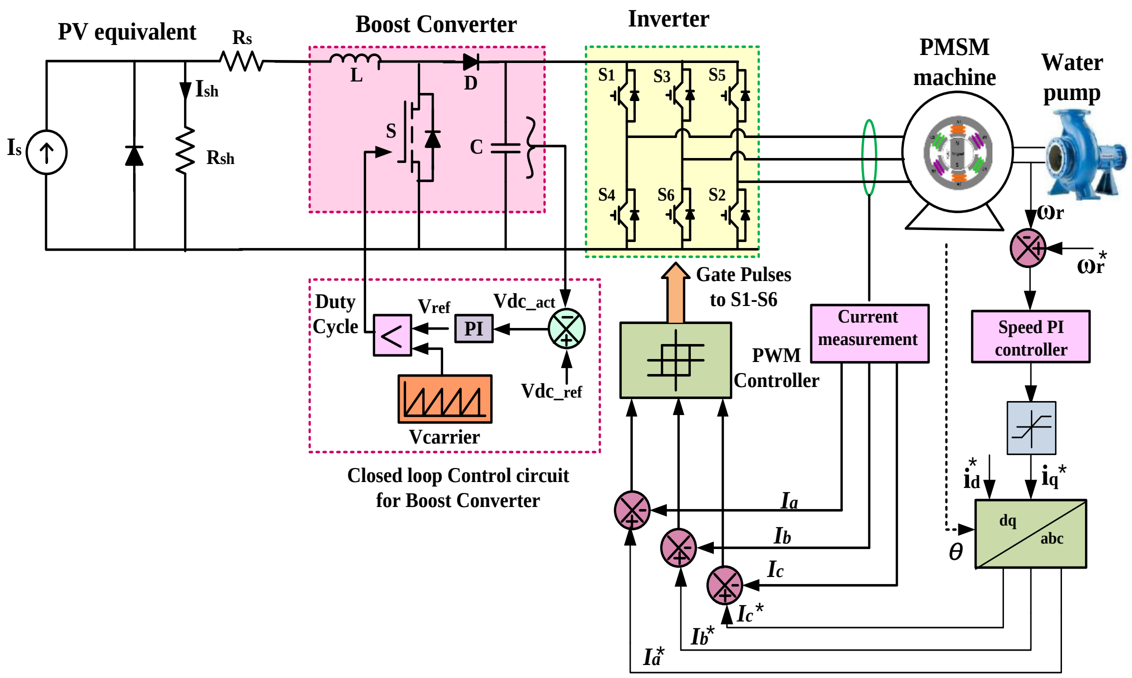

Figure 6: Schematic structure of PV with boost converter fed closed-loop PMSM drive

Figure 6 depicts the schematic arrangement of PV with boost converter fed closed-loop PMSM drive. Photo-voltaic equivalent circuit is the main source to the PMSM drive. Photo-voltaic system generates electricity from the sun-light. PV system absorbs photon energy and allows current to flow by breaking the junction barrier. The generated output of PV system is low-voltage DC power and a DC-DC (boost) converter is used to step-up the voltage level of the PV output.

Boost converter (for stepping up the voltage output of PV system) is operated in closed-loop mode. The output of the boost converter is sensed across output capacitor of boost converter and is compared to reference DC voltage. The error of DC voltage is fed to PI controller where it produces reference voltage signal. The reference voltage signal is compared to carrier signal the comparator which produces controlling pulses to the high frequency switch in boost converter.

The DC output of the PV with closed-loop boost converter is fed to the converter (inverter) of PMSM drive. The inverter excites the stator windings of the PMSM to generate sinusoidal flux. The power switches of the inverter are generated from closed-loop control of the drive system. Hall sensors sense three phase motor currents. Reference motor speed (ω*) is compared to actual motor speed. Speed error is processed to PI controller which gives out reference Iq component. Reference Id and Iq components are converted to ‘abc’ frame using inverse Park’s transformation and are compared to actual currents from line. The errors in currents are fed to PWM controller to produce gate pulses to six switches of inverter circuit.

3. CLOSED-LOOP PV WITH INTERLEAVED BOOST CONVERTER FED PMSM

3.1 Interleaved Boost converter

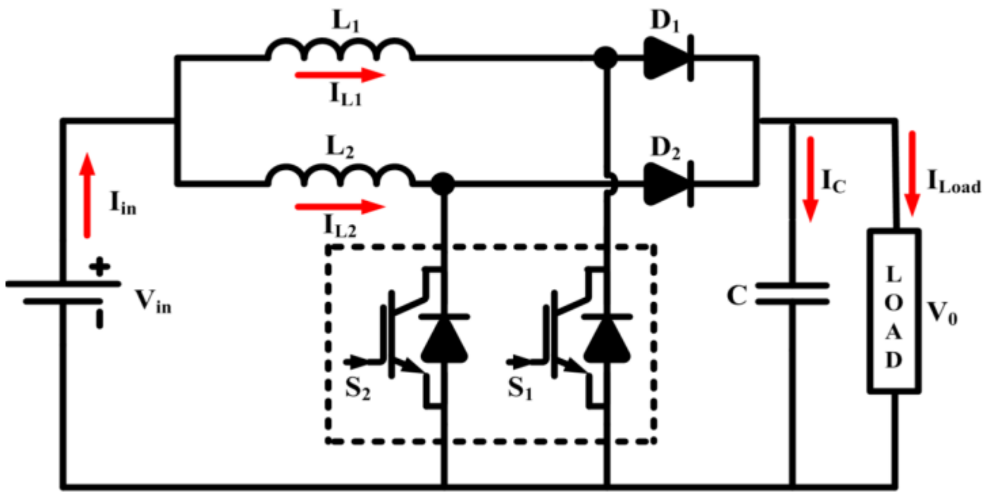

Figure 7: Interleaved Boost converter

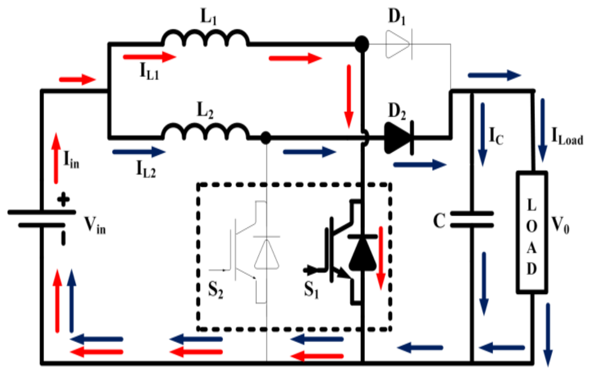

Fig 8: Interleaved Boost converter when switch S1 is ON

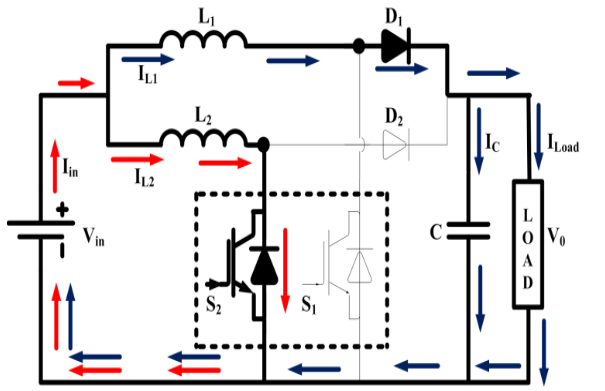

Fig 9: Interleaved Boost converter when switch S2 is ON

The technique of splitting (paralleling) the current path is called interleaving. The two inductors in interleaved structure share the input current. Figure 7 shows the two-phase interleaved boost converter. Single inductor in the conventional boost converter is replaced with two parallel inductors in interleaved structure. To diminish the current ripples the two inductors are phase shifted by 180^0. Interleaved boost converter circuit consists of two inductors L1 and L2, diodes D1 and D2, two switches S1 and S2 and a capacitor C. the two inductors in interleaved structure are rated same and are used to transfer the input energy to output. Equal rated inductors shares the input current which reduces the inductor rating and the rating of the switch. Interleaved Boost converter when only switch S1 is ON and Interleaved Boost converter when only switch S2 is ON is shown in figure 8 and figure 9 respectively. Equations corresponding to interleaved boost converter are shown below.

$$I_{Lavg} = \frac{0.5 * I_{out}}{1 - D_{max}} \quad (6)$$

Where, $D_{max} = \left. \frac{V_{out} + V_d - V_{in(min)}}{V_{out} + V_d - V_{on}} \right.$ (7)

Assuming suitable frequency for switching, inductor can be calculated from

$$L = \frac{(V_{in(min)} - V_{on}) * D_{max} * (1 - D_{max})}{f_s * I_{out}} \quad (8)$$

3.2 PV with interleaved boost converter fed closed-loop PMSM drive

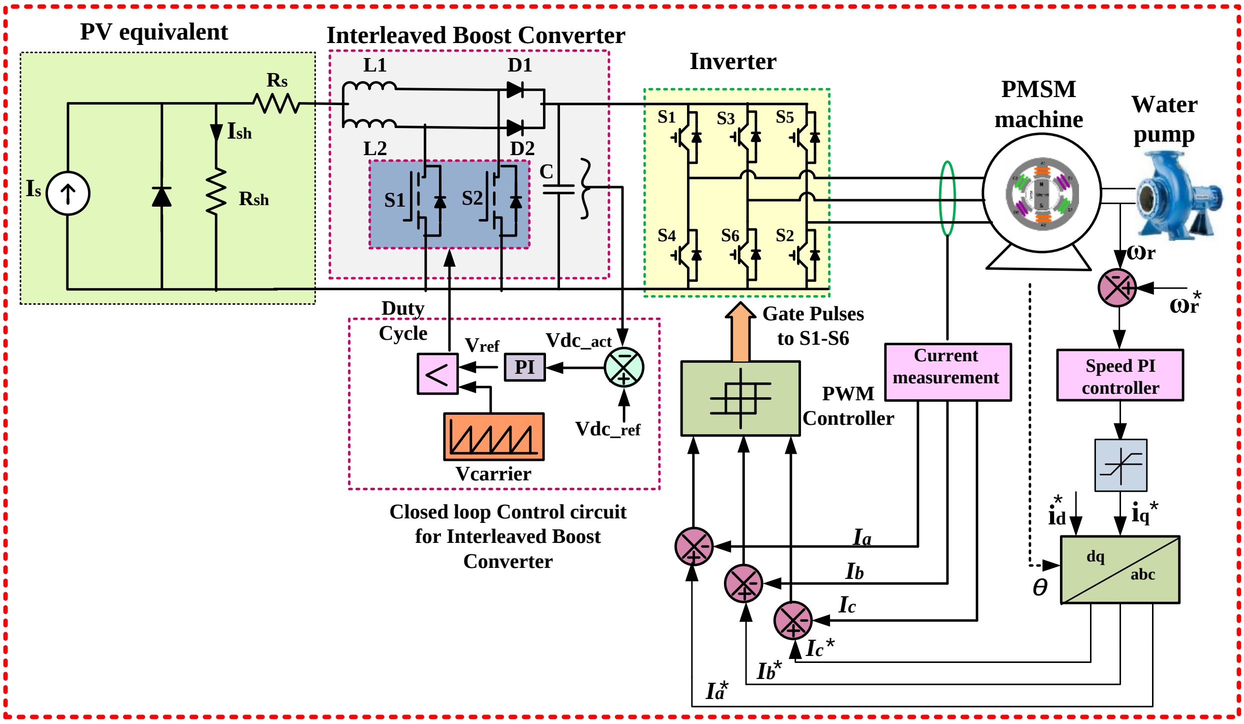

Figure 10: Schematic structure of PV with boost converter fed closed-loop PMSM drive

Figure 10 depicts the schematic arrangement of PV with interleaved boost converter fed closed-loop PMSM drive. Photo-voltaic equivalent circuit is the main source to the PMSM drive. Interleaved Boost converter (for stepping up the voltage output of PV system) is operated in closed-loop mode. The output of the interleaved boost converter is sensed across the output capacitor and is compared to reference DC voltage. The error of DC voltage is fed to PI controller where it produces reference voltage signal. The reference voltage signal is compared to carrier signal the comparator which produces controlling pulses to the high frequency switch in boost converter.

The DC output of the PV with closed-loop interleaved boost converter is fed to the converter (inverter) of PMSM drive. The inverter excites the stator windings of the PMSM to generate sinusoidal flux. The power switches of the inverter are generated from closed-loop control of the drive system. Hall sensors sense three phase motor currents. Reference motor speed (ω*) is compared to actual motor speed. Speed error is processed to PI controller which gives out reference Iq component. Reference Id and Iq components are converted to ‘abc’ frame using inverse Park’s transformation and are compared to actual currents from line. The errors in currents are fed to PWM controller to produce gate pulses to six switches of inverter circuit.

4. CLOSED-LOOP PV WITH HYBRID BOOST CONVERTER FED PMSM

4.1 Hybrid Boost converter

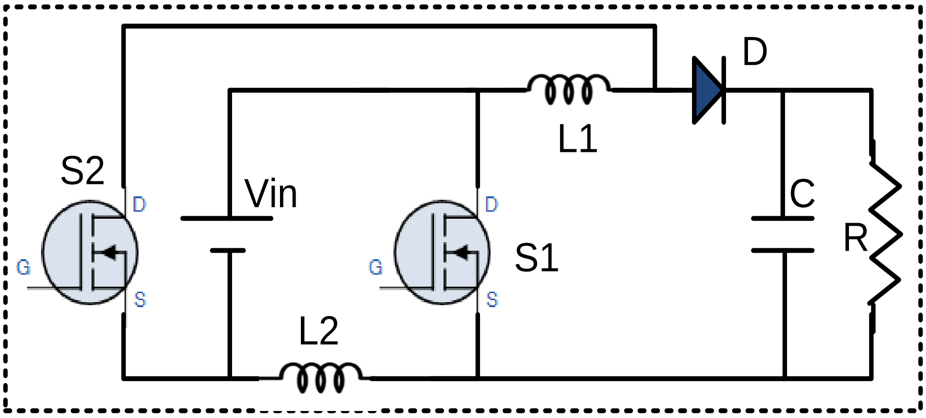

Figure 11: Hybrid Boost converter

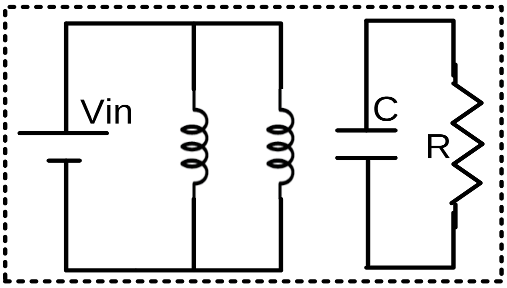

Figure 12: Hybrid boost converter when both S1 & S2 are ON

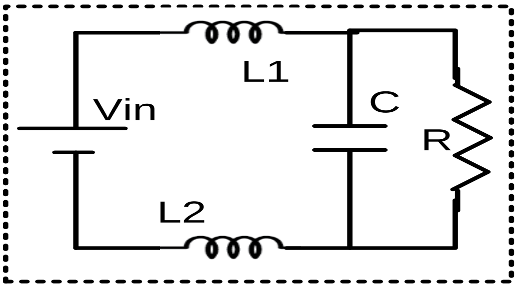

Figure 12: Hybrid boost converter when both S1 & S2 are ON

Figure 11 shows the hybrid boost converter and it consists of two switches S1 and S2. Also it consists of two inductor coils L1 and L2, a diode D and a capacitor C. Resistive load is connected across the load terminals. The circuit of the hybrid boost converter when both the switches S1 and S2 in ON condition is shown in figure 12 and hybrid boost converter when both the switches S1 and S2 in OFF condition is shown in figure 13.

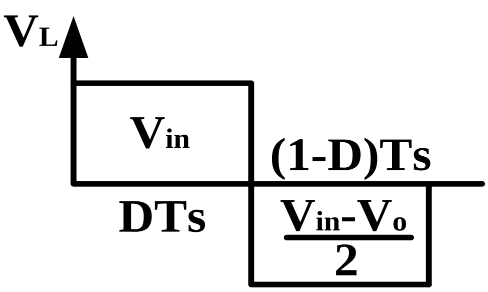

Figure 13: Timing diagram of hybrid boost converter

When both the switches are ON, the source voltage is present across each inductor and both L1 and L2 are charged up to the voltage level of input source. During this time period, the load is driven by the capacitor.

$$Vin = V_{L1} = V_{L2} \quad (9)$$

When the switches S1 and S2 are in OFF condition, the input current flows from source through inductor (L1), capacitor (C) and inductor (L2). Since already the inductors are charged up to the level of input value, the capacitor is charged to thrice the value of input source.

Making the average voltage across the inductor yields the formulation of voltage gain for hybrid boost converter.

$$\frac{V_{in} * DT_s + \left(\frac{V_{in} - V_0}{2}\right)(1-D)T_s}{T_s} = 0 \quad (10)$$

$$V_{gainproposed} = \frac{V_0}{V_{in}} = \frac{1+D}{1-D} \quad (11)$$

In spite of having more components in the hybrid boost converter, the gain is very high for the same duty ratio compared to conventional boost converter.

4.2 PV with Hybrid boost converter fed closed-loop PMSM drive

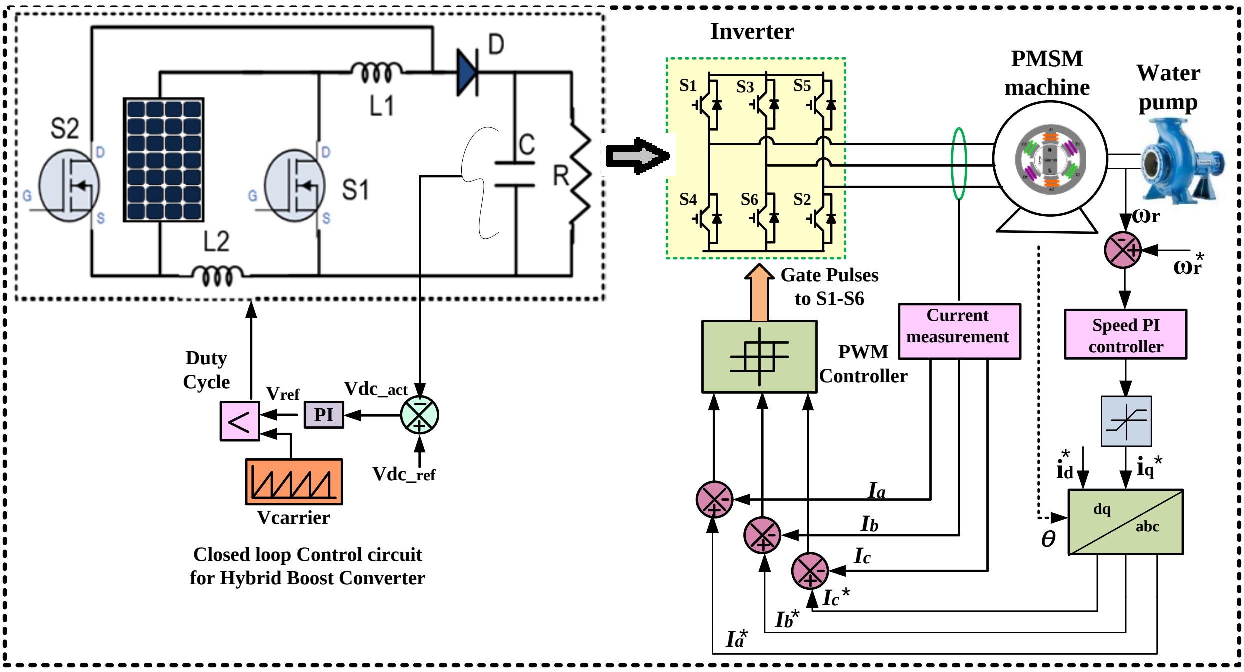

Figure 14: Schematic structure of PV with hybrid boost converter fed closed-loop PMSM drive

Figure 14 depicts the schematic arrangement of PV with hybrid boost converter fed closed-loop PMSM drive. The output of the hybrid boost converter is sensed across the output capacitor and is compared to reference DC voltage. The error of DC voltage is fed to PI controller where it produces reference voltage signal. The reference voltage signal is compared to carrier signal the comparator which produces controlling pulses to the high frequency switch in boost converter.

The DC output of the PV with closed-loop interleaved boost converter is fed to the converter (inverter) of PMSM drive. The inverter excites the stator windings of the PMSM to generate sinusoidal flux. The power switches of the inverter are generated from closed-loop control of the drive system. Hall sensors sense three phase motor currents. Reference motor speed (ω*) is compared to actual motor speed. Speed error is processed to PI controller which gives out reference Iq component. Reference Id and Iq components are converted to 'abc' frame using inverse Park's transformation and are compared to actual currents from line. The errors in currents are fed to PWM controller to produce gate pulses to six switches of inverter circuit.

5. RESULTS AND ANALYSIS

5.1 Open loop hybrid boost converter

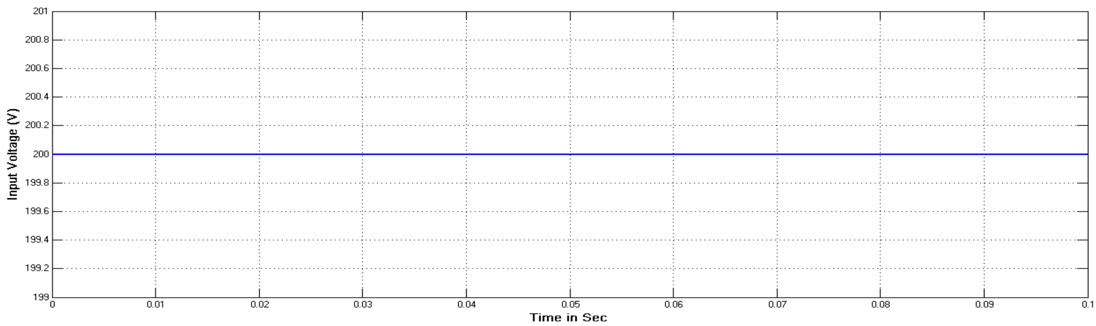

Figure 15: Input voltage to the hybrid boost converter

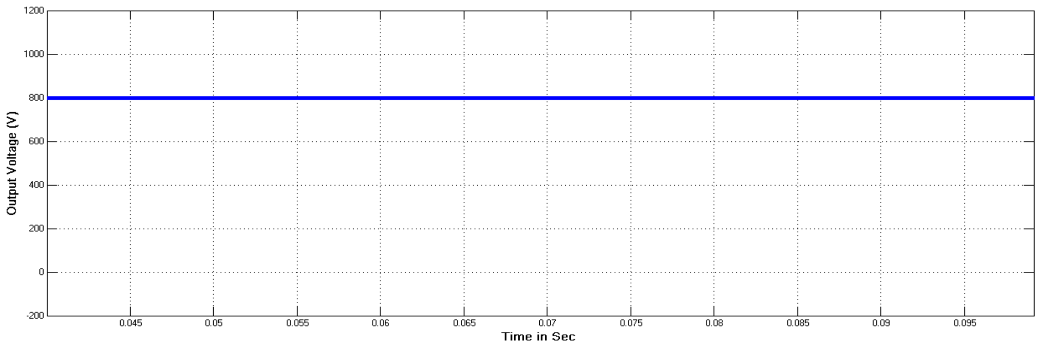

Figure 16: Output voltage to the hybrid boost converter

Figure 15 illustrates the input voltage to the hybrid boost converter (output of the PV system) of 200V and the output voltage 800V from the hybrid boost converter is shown in figure 16.

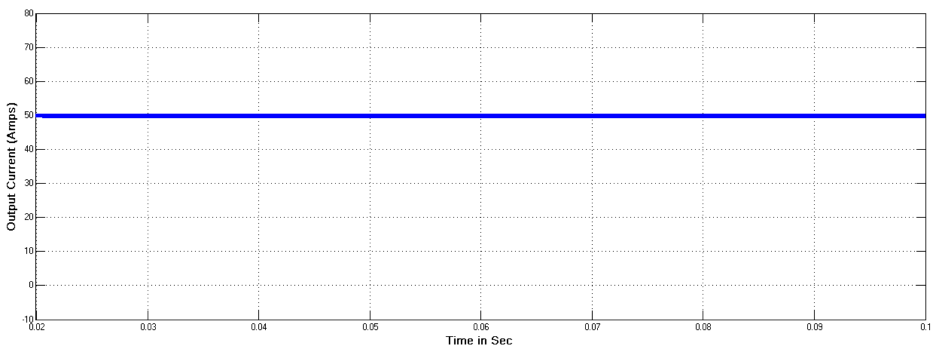

Figure 17: Output current of the hybrid boost converter

Figure 17 shows the output current passing through the load of hybrid boost converter. The current passing through the load is 50A.

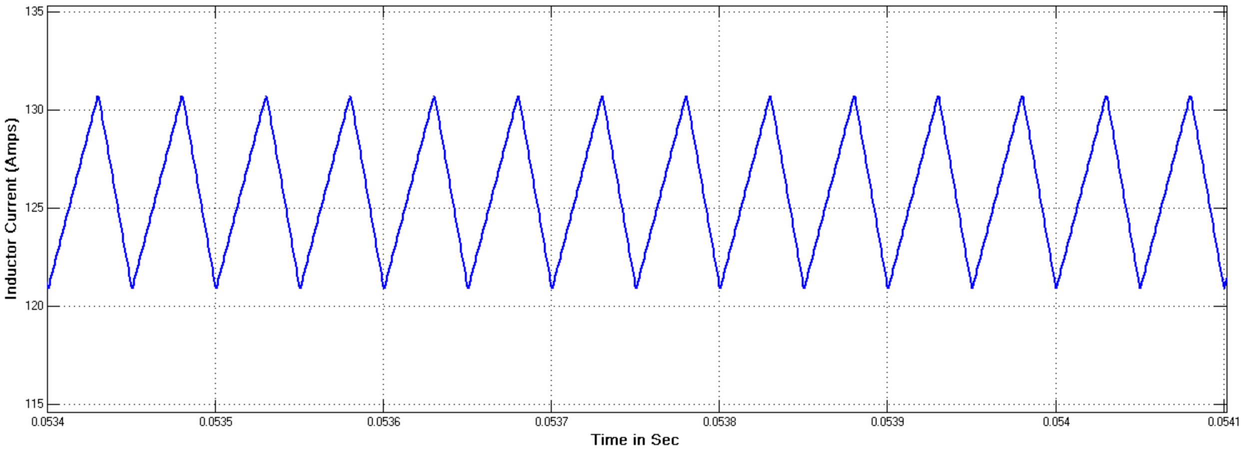

Figure 18: Inductor-1 ripple current of hybrid boost converter

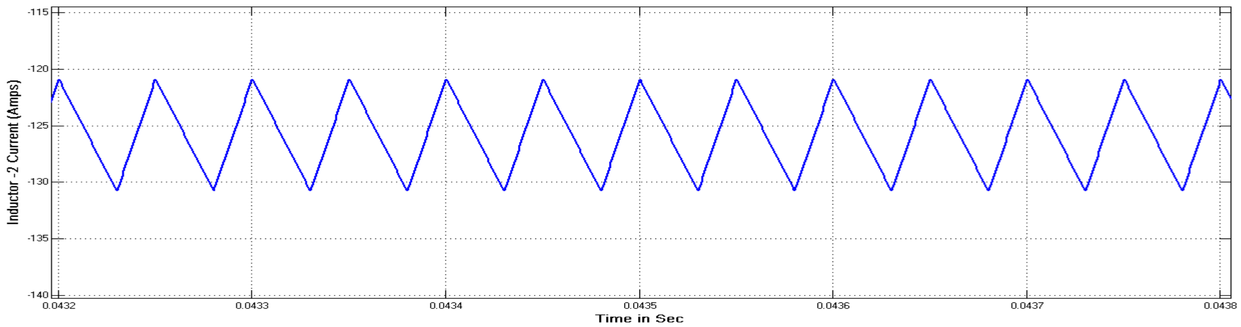

Figure 19: Inductor-2 ripple current of hybrid boost converter

Figure 18 and figure 19 shows the ripple current in inductor-1 an inductor-2 of hybrid boost converter. There is a ripple current of 10A in inductors of hybrid boost converter.

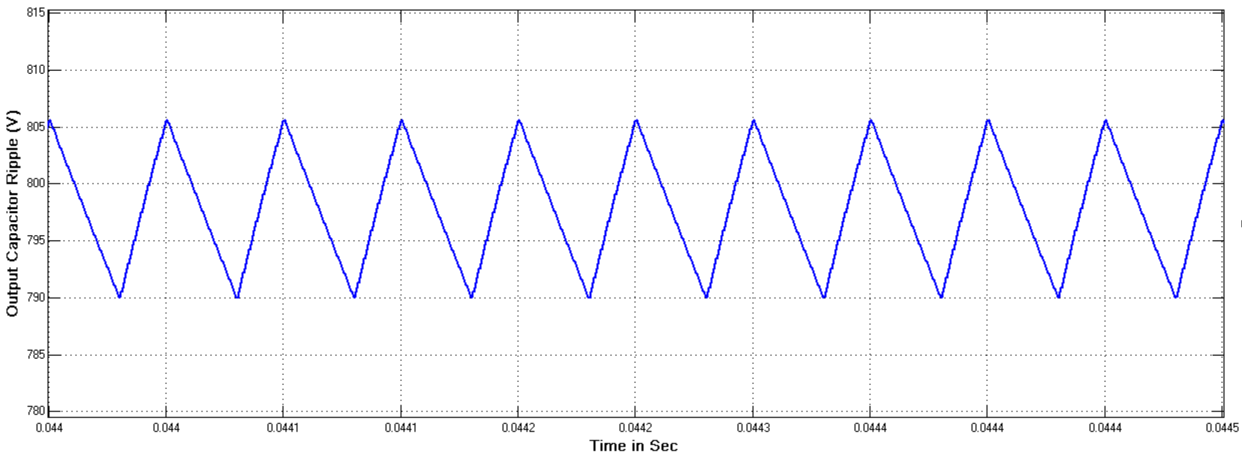

Figure 20: Output capacitor voltage ripple of hybrid boost converter

Figure 20 shows the voltage ripple in output capacitor of hybrid boost converter. There is a ripple of 15V in capacitor since the converter is operated in open loop mode.

5.2 Closed-loop speed control of PV with Boost converter fed PMSM drive

5.2.1 Fixed speed condition

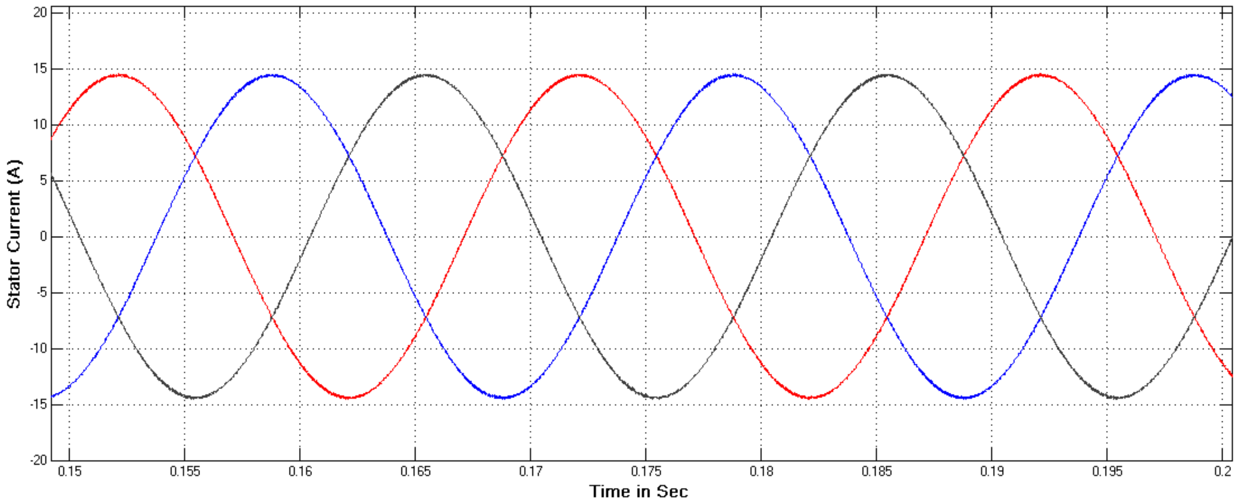

Figure 21: Stator current to PMSM

Figure 21 shows the three-phase stator current to PMSM machine. Three-phase stator currents fed to stator windings of PMSM are balanced and sinusoidal in shape with constant peak of 15A.

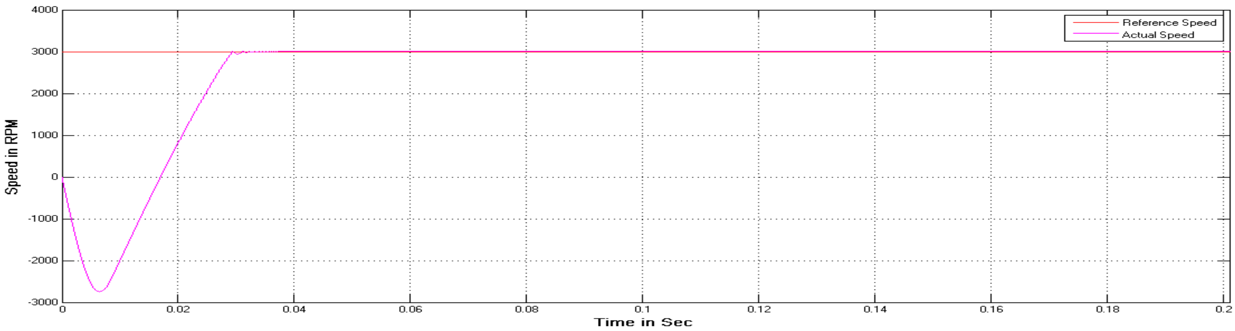

Figure 22: Speed of PMSM

Figure 22 shows the speed curve of PMSM drive. Reference speed command of 3000RPM is set in closed-loop drive operation and the actual speed curve seems to run at set speed. Both reference speed and actual speed of PMSM are shown in figure 22. PMSM reaches reference or set speed at 0.031 seconds.

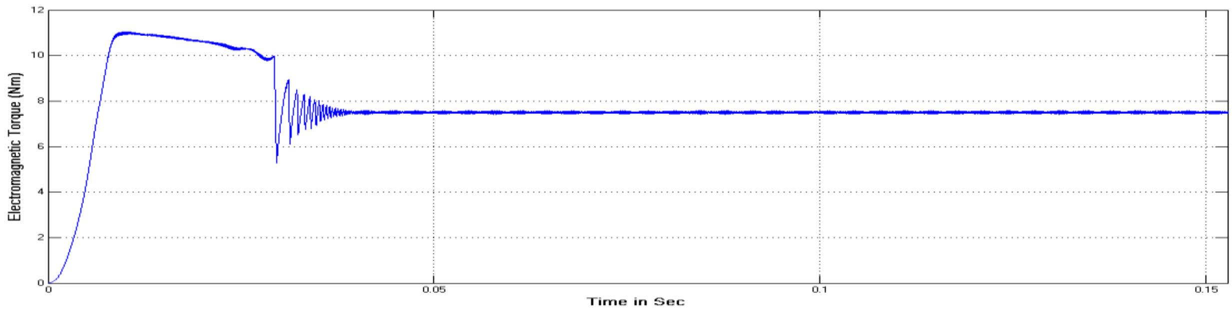

Figure 23: Torque of PMSM

Figure 23 illustrates torque of PMSM. Torque of 7.5A is impressed on PMSM to run PMSM at set speed. Torque curve remains constant.

5.2.2 Variable speed condition

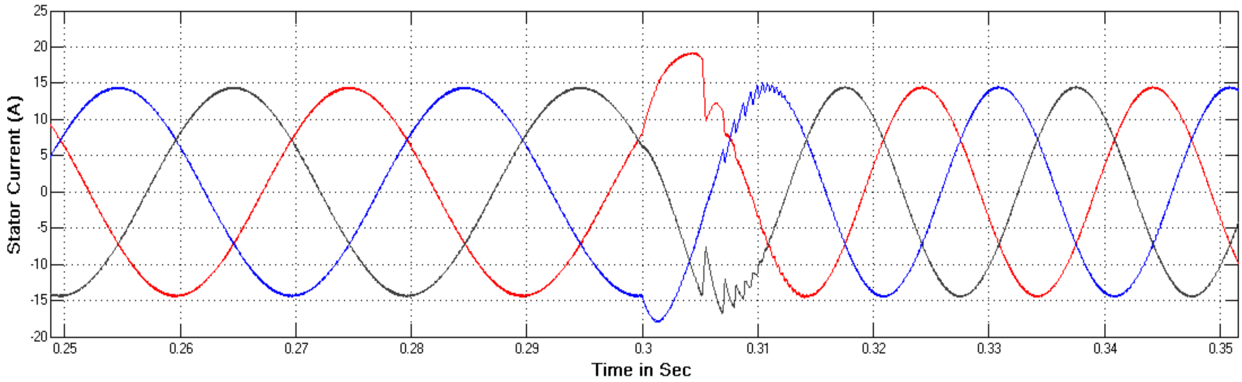

Figure 24: Three-phase Stator currents of PMSM

Figure 24 shows the three-phase stator currents of PMSM drive. Three-phase stator currents are balanced, sinusoidal in shape with constant peak of 15A. Apart from slight disturbance in three-phase signal at the (0.3 seconds) period of speed change command, three-phase stator currents of PMSM are maintained at constant peak and balanced. Frequency of the stator currents increases as speed increases after 0.3 seconds.

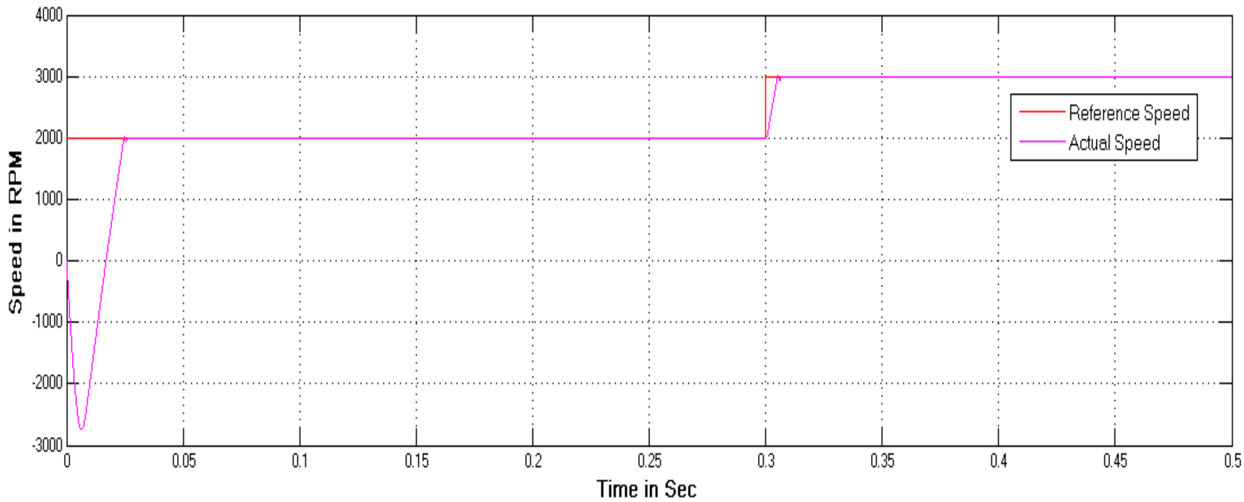

Figure 25: Speed of PMSM

Figure 25 shows the speed curve of PMSM drive. Reference speed command of 2000RPM is set in closed-loop drive operation initially. At 0.3 seconds, set speed is varied to run PMSM at 3000RPM. Actual speed curve seems to run at set speed 2000RPM initially and later at 3000RPM following the reference curve. Both reference speed and actual speed of PMSM are shown in figure 25.

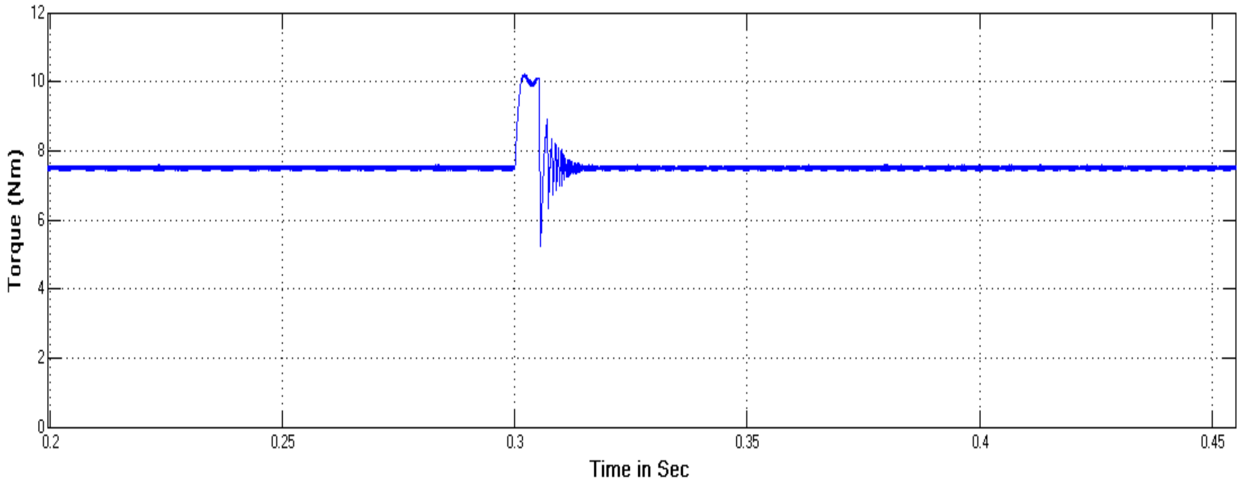

Figure 26: Torque of PMSM

Figure 26 illustrates torque of PMSM. Torque of 7.5A is impressed on PMSM to run PMSM at set speed. Torque remains constant apart from distortion at speed varied time at 0.3 seconds.

5.3 Closed-loop speed control of PV with Interleaved Boost converter fed PMSM drive

5.3.1 Fixed speed condition

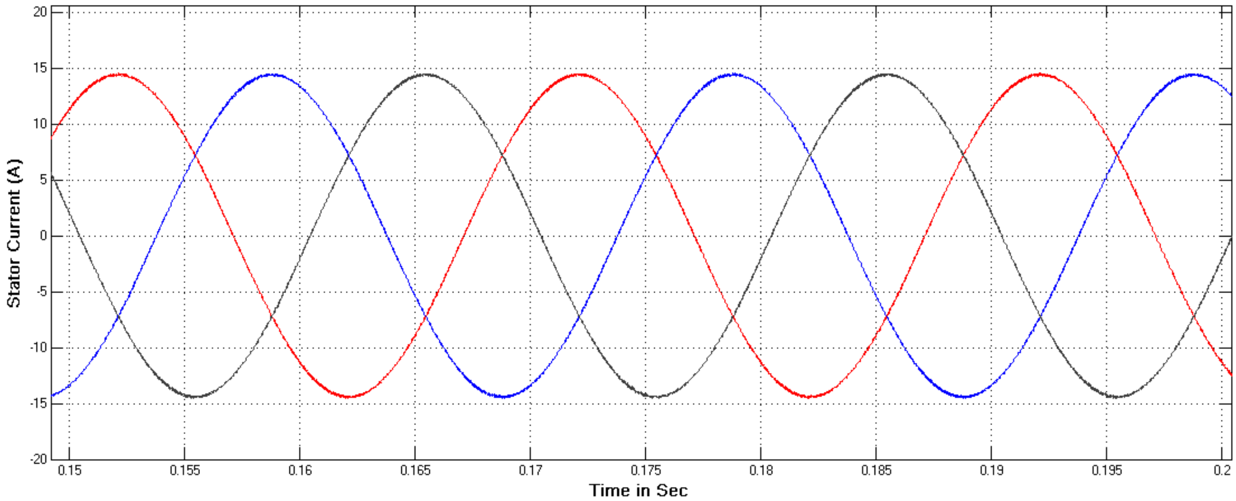

Figure 27: Stator current to PMSM

Figure 27 shows the three-phase stator current to PMSM machine fed from interleaved boost converter. Three-phase stator currents fed to stator windings of PMSM are balanced and sinusoidal in shape with constant peak of 15A.

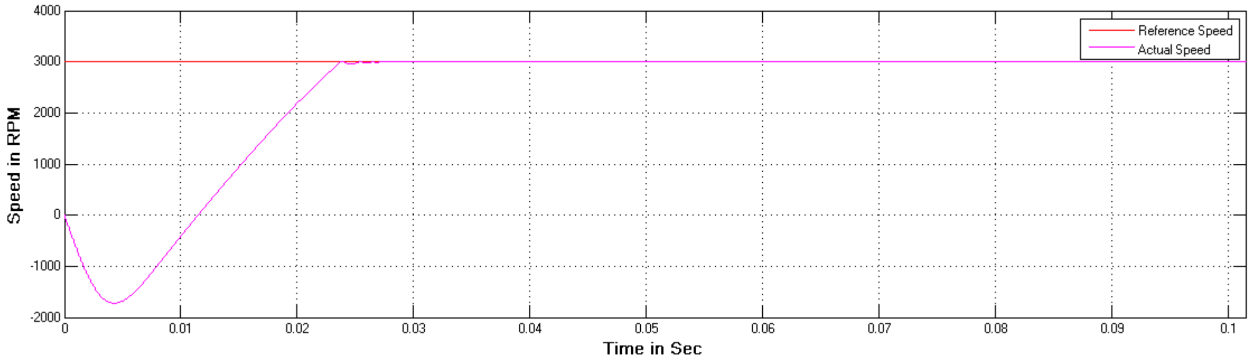

Figure 28: Speed of PMSM

Figure 28 shows the speed curve of PMSM drive. Reference speed command of 3000RPM is set in closed-loop drive operation and the actual speed curve seems to run at set speed. Both reference speed and actual speed of PMSM are shown in figure 28. PMSM drive fed from interleaved boost converter reaches set speed at 0.025 seconds.

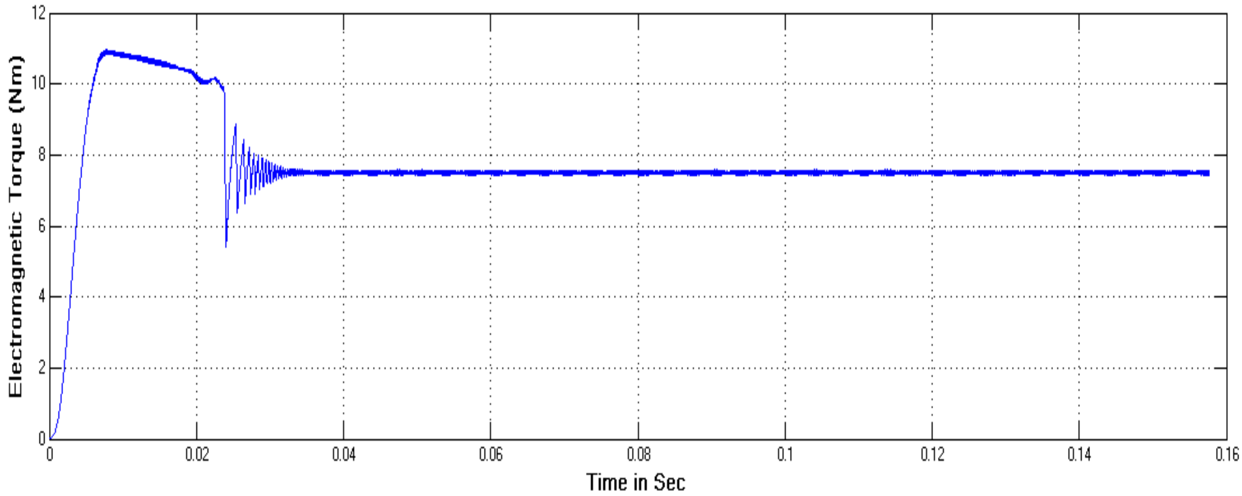

Figure 29: Torque of PMSM

Figure 29 illustrates torque of PMSM. Torque of 7.5A is impressed on PMSM to run PMSM at set speed. Torque curve remains constant.

5.3.2 Variable speed condition

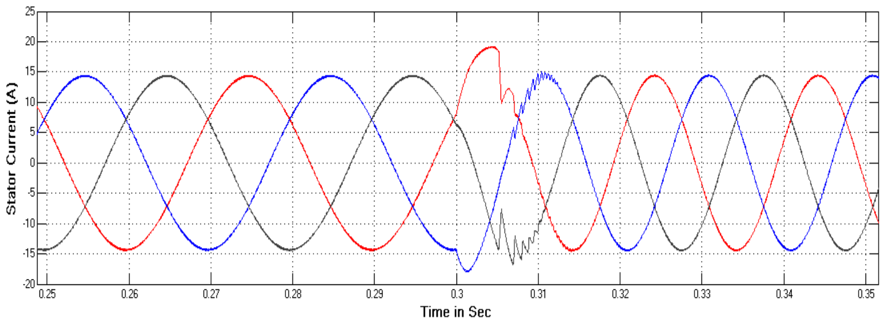

Figure 30: Three-phase Stator currents of PMSM

Figure 30 shows the three-phase stator currents of PMSM drive. Three-phase stator currents are balanced, sinusoidal in shape with constant peak of 15A. Apart from slight disturbance in three-phase signal at the (0.3 seconds) period of speed change command, three-phase stator currents of PMSM are maintained at constant peak and balanced. Frequency of the stator currents increases as speed increases after 0.3 seconds.

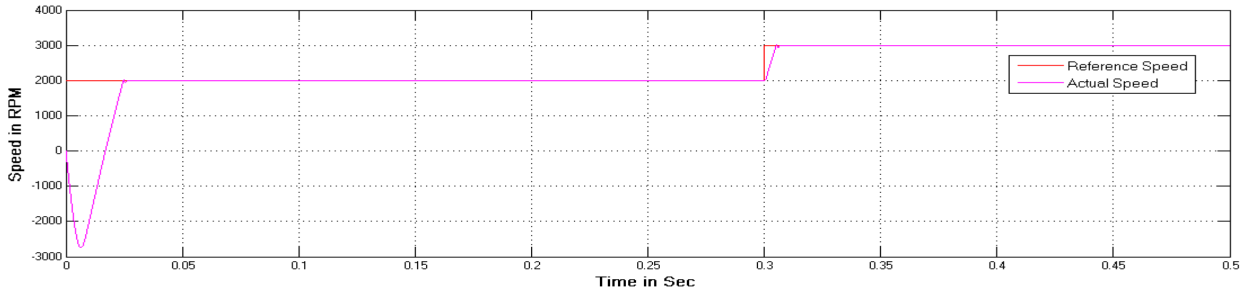

Figure 31: Speed of PMSM

Figure 31 shows the speed curve of PMSM drive. Reference speed command of 2000RPM is set in closed-loop drive operation initially. At 0.3 seconds, set speed is varied to run PMSM at 3000RPM. Actual speed curve seems to run at set speed 2000RPM initially and later at 3000RPM following the reference curve. Both reference speed and actual speed of PMSM are shown in figure 31.

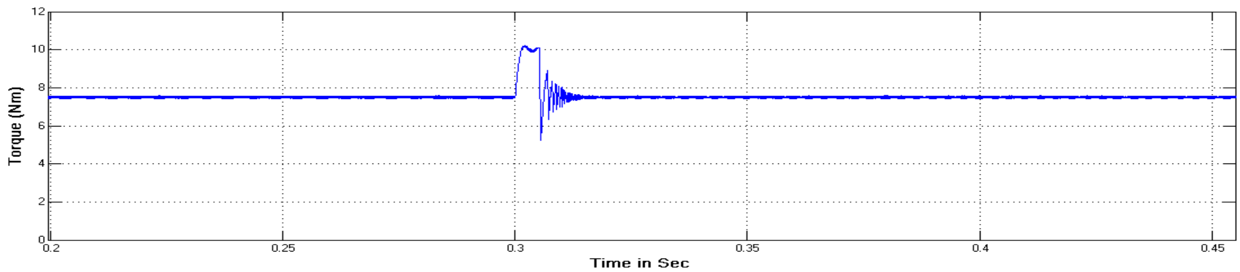

Figure 32: Torque of PMSM

Figure 32 illustrates torque of PMSM. Torque of 7.5A is impressed on PMSM to run PMSM at set speed. Torque remains constant apart from distortion at speed varied time at 0.3 seconds.

5.4 Closed-loop speed control of PV with Hybrid Boost converter fed PMSM drive

5.4.1 Fixed speed condition

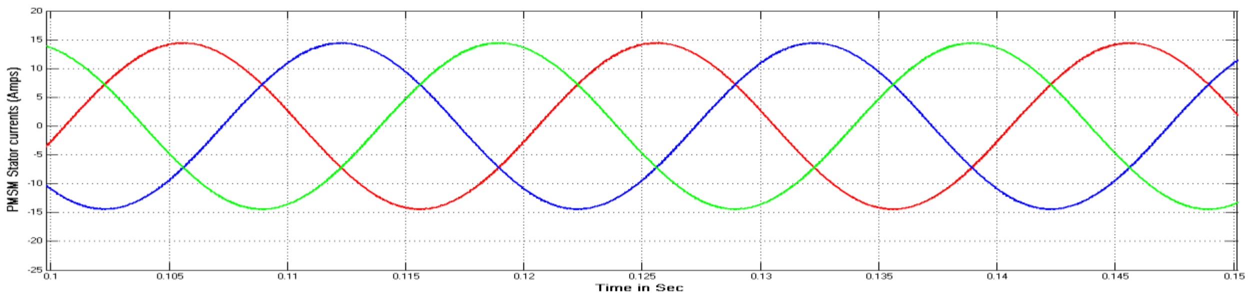

Figure 33: Stator currents of PMSM

Figure 33 shows the three-phase stator current to PMSM machine fed from hybrid boost converter. Three-phase stator currents fed to stator windings of PMSM are balanced and sinusoidal in shape with constant peak of 15A.

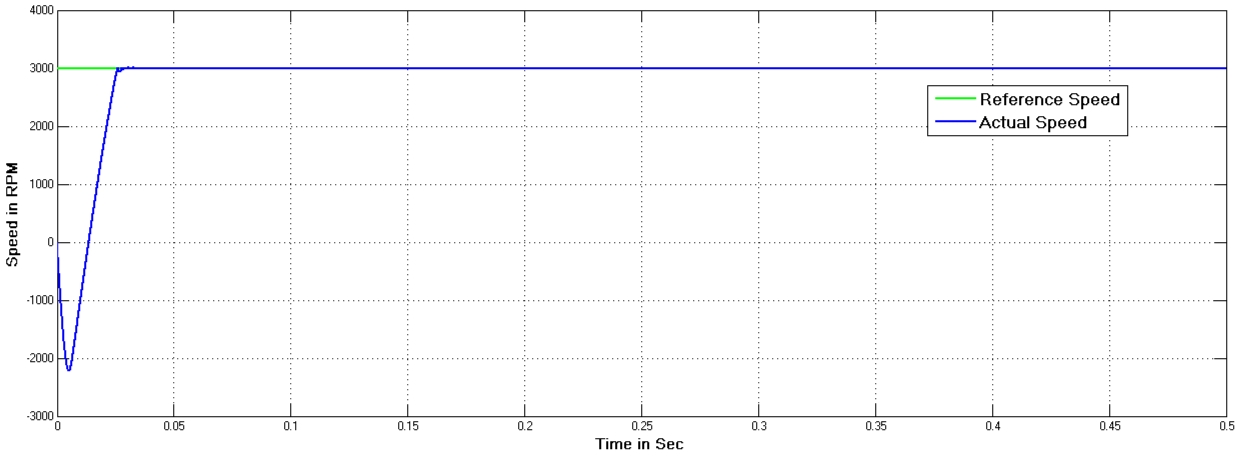

Figure 34: Speed of PMSM

Figure 34 shows the speed curve of PMSM drive. Reference speed command of 3000RPM is set in closed-loop drive operation and the actual speed curve seems to run at set speed. Both reference speed and actual speed of PMSM are shown in figure 34. PMSM drive fed from hybrid boost converter reaches set speed at 0.025 seconds.

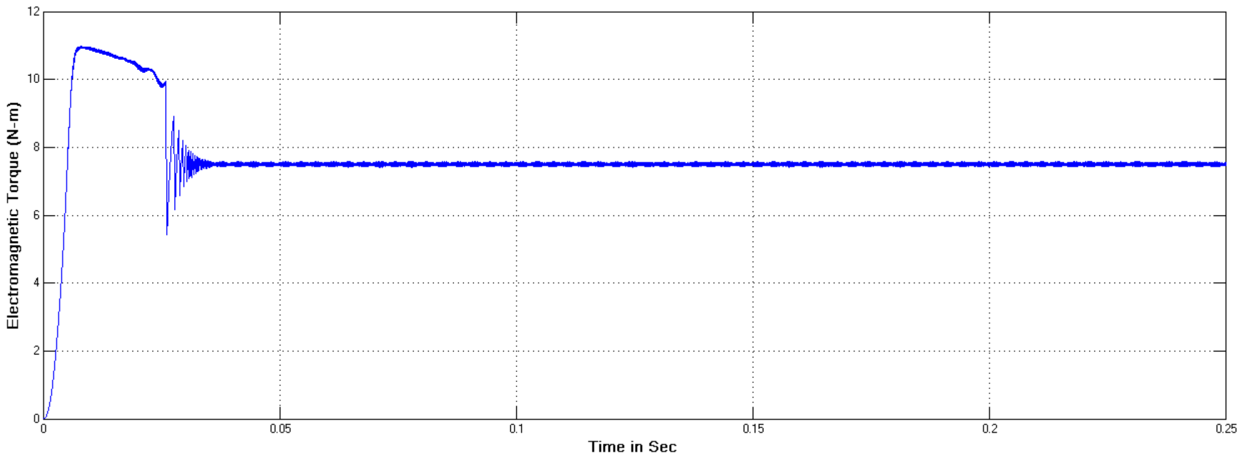

Figure 35: Torque of PMSM

Figure 35 illustrates torque of PMSM. Torque of 7.5A is impressed on PMSM to run PMSM at set speed. Torque curve remains constant.

5.4.2 Variable speed condition

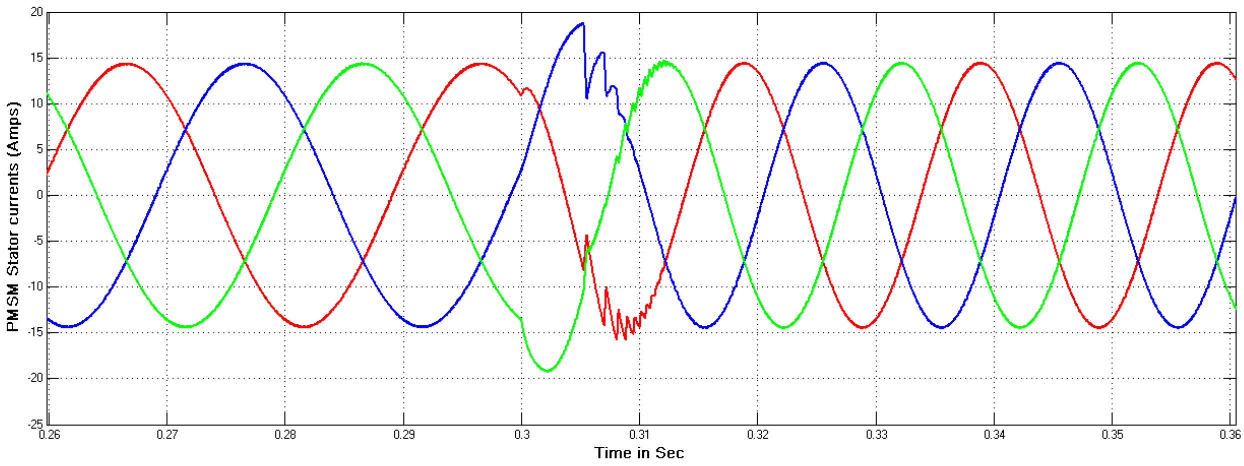

Figure 36: Three-phase Stator currents of PMSM

Figure 36 shows the three-phase stator currents of PMSM drive. Three-phase stator currents are balanced, sinusoidal in shape with constant peak of 15A. Apart from slight disturbance in three-phase signal at the (0.3 seconds) period of speed change command, three-phase stator currents of PMSM are maintained at constant peak and balanced. Frequency of the stator currents increases as speed increases after 0.3 seconds.

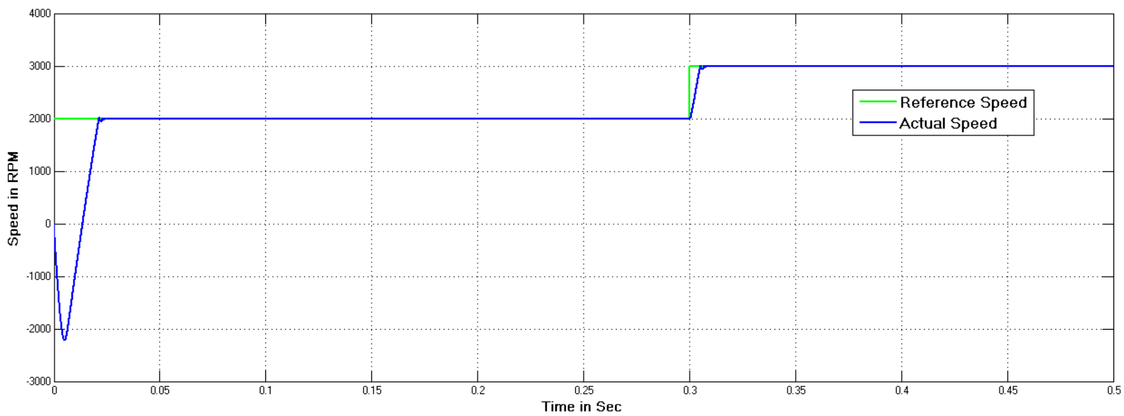

Figure 37: Speed of PMSM

Figure 37 shows the speed curve of PMSM drive. Reference speed command of 2000RPM is set in closed-loop drive operation initially. At 0.3 seconds, set speed is varied to run PMSM at 3000RPM. Actual speed curve seems to run at set speed 2000RPM initially and later at 3000RPM following the reference curve. Both reference speed and actual speed of PMSM are shown in figure 37.

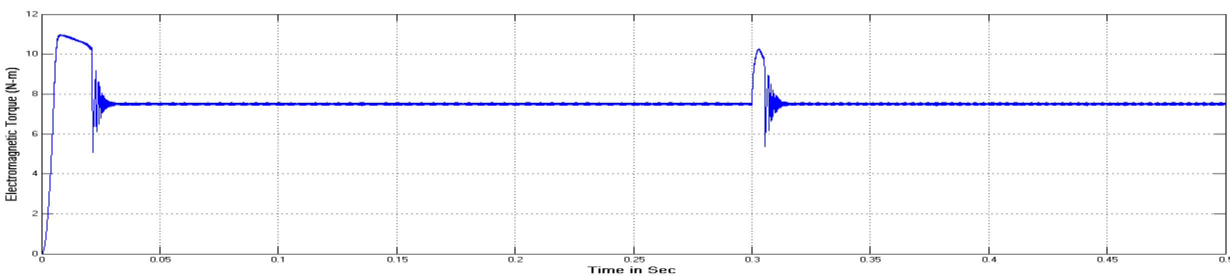

Figure 38: Torque of PMSM

Figure 38 illustrates torque of PMSM. Torque of 7.5A is impressed on PMSM to run PMSM at set speed. Torque remains constant apart from distortion at speed varied time at 0.3 seconds. Comparative analysis of different non-isolated DC-DC converters is differentiated in table-1 and table-2.

Table-1: Voltage gain

Converter Type	**Voltage Gain**	**For 50% Duty ratio**
Boost Converter	$\frac{1}{1-D}$	Vout=2*Vin
Interleaved Boost Converter	$\frac{1}{1-D}$	Vout=2*Vin
Hybrid Boost Converter	$\frac{1+D}{1-D}$	Vout=3*Vin

Table-2: Speed – final settling time comparison

	Conventional Boost Converter	**Interleaved Boost Converter**	**Hybrid Boost Converter**
Speed settling time (Sec)	0.031 Sec	0.025 Sec	0.025 Sec

6. CONCLUSION

This paper presents the analysis of PV with non-isolated DC-DC converter fed permanent magnet synchronous motor drive. Conventional boost converter, interleaved boost converter and hybrid boost converter type of non-isolated DC-DC converters are analyzed with PMSM drive. DC-DC converters are operated in closed-loop mode to give out precise output and to gain the voltage output of PV system. Speed control of PMSM is operated in closed-loop mode and analyzed for fixed speed and variable speed conditions. Hybrid boost converter, in spite of having more components, the gain is very high for the same duty ratio compared to conventional boost converter. Open-loop hybrid boost converter is simulated and results are shown. Hybrid converter taking input from PV system and feeding closed-loop PMSM drive is simulated and valid for fixed and variable speeds. For the same duty ratio, compared to conventional boost and interleaved boost converters, hybrid boost converter gives more output voltage gain as shown in table-1. Speed performance of PV with hybrid boost converter fed PMSM drive is quite satisfactory.

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