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Performance of Brushless DC Drive with Single Current Sensor Fed from PV with High Voltage-Gain DC-DC Converter

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ABSTRACT

This paper presents the performance of Brushless DC (BLDC) Motor drive with only one positioning sensor instead of three conventional sensors. The three sensor units are replaced with a single stator current sensor unit in DC bus which further reduces the cost increasing the reliability of the drive system. Using a single sensor in stator requires minimum electronic equipment for the purpose of measurement process. This paper evolves the BLDC motor drive fed from PV system. A high voltage-gain DC-DC converter is presented in this paper to step-up the voltage from PV system. The appropriateness of PV fed BLDC motor drive is verified for variable increamental speed with fixed torque and variable decremental speed with fixed torque operating conditions. BLDC motor drive performance is also performed for variable torque with fixed speed working condition. The proposed system and results are developed using MATLAB/SIMULINK software.

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1. INTRODUCTION

Technology is for human convenience and innovation of electric motors gave scope to reduce the efforts put in by human mankind in many applications especially in industries. Electric motor is an electro-mechanical device which converts electrical energy to mechanical energy. Motors can be broadly classified in to DC type and AC type of motors. DC motor exhibits fine speed characteristic which are very much a constraint in many of the applications. DC motors are simple in construction and has good torque characteristics. Commutation is done with the help of brush-commutator assembly. Brush is a static device which collects current from or in to machine via commutator. Commutator is a rotating device which transforms supplied DC to alternating type to armature. Due to the presence of commutator and brush assembly in conventional DC motors, additional losses are produced and with resulting sparks. This phenomenon affects the overall system efficiency. To improve the system efficiency and to reduce additional losses produced due to brush-commutator assembly, brushless DC motors are developed constructed without the need of brushes and commutator for commutation [1-3].

Brushless DC (BLDC) motors are synchronous motors developed eliminating brush-commutator assembly. BLDC motor is constructed with armature on its stator and permanent magnets on its rotor [4-5]. BLDC motor does not consist of windings on both stator and rotor thus consuming less copper and less reactive power absorption as compared with induction motor which has windings on both stator and rotor. Solid state electronic switches carries electrical commutation in BLDC motor excluding the use of brush-commutator assembly as in conventional DC motors. This type of construction can improve system efficiency with increased performance. Stator windings of BLDC motor are excited with alternating three-phase currents producing rotating magnetic field. Rotating magnetic field interacts with the rotor flux and torque is exerted on rotor. BLDC motor can run at high speeds with low acoustic noise. High efficiency and reliability also makes BLDC motor a better choice for many applications [6-7].

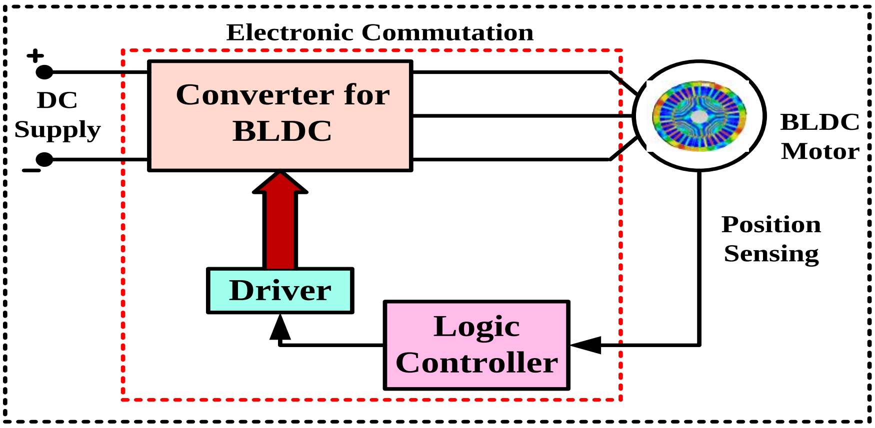


Figure 1. Block diagram of BLDC motor

Figure 1 shows the block diagram of BLDC motor with electronic commutator and logic controller. BLDC is supplied from DC supply and electronic commutator converts the DC supply given to BLDC to AC as commutator in conventional machine. Hall sensors sense the position of the rotor and sends position signal to controller in which control action takes place [5-6]. The controller produces gate pulses to solid-state switches in converter through driver circuit.

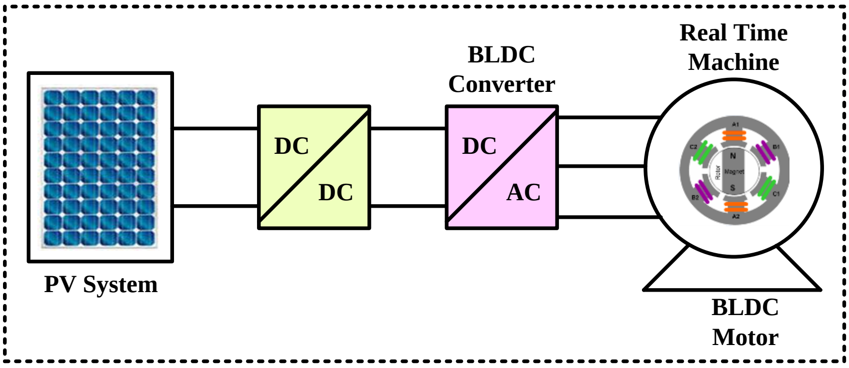


Figure 2. PV cell Fed BLDC motor

The DC source to be fed to BLDC motor as an input is chosen to be photo-voltaic (PV) system in this paper. P-N junction layer arranged in a specific manner forms a PV cell and when photons from solar energy falls on PV cell, electrons in PV cell tries to move crossing the barrier junction giving rise to current flow. Solar energy is a type of renewable energy source freely available from universe and the electrical energy generated from this type of resource is inexhaustible. PV system generates DC type of electrical power and is of low voltage. The low voltage output from solar PV system is insufficient to drive any system and thus requires a voltage booster generally a DC-DC converter. High gain DC-DC converter is employed in this paper for boosting the low voltage DC output from PV system. The complete schematic arrangement of PV cell Fed BLDC motor is shown in Figure 2.

This paper presents the performance of Brushless DC (BLDC) Motor drive with only one positioning sensor instead of three conventional sensors [7-10]. The three sensor units are replaced with a single stator current sensor unit in DC bus which further reduces the cost increasing the reliability of the drive system [11-14]. Using a single sensor in stator requires minimum electronic equipment for the purpose of measurement process. This paper evolves the BLDC motor drive [15-17] fed from PV system. A high voltage-gain DC-DC converter is presented in this paper to step-up the voltage from PV system. The appropriateness of PV fed BLDC motor drive is verified for variable increamental speed with fixed torque and variable decremental speed with fixed torque operating conditions. BLDC motor drive performance is also performed for variable torque with fixed peed working condition. The proposed system and results are developed using MATLAB/SIMULINK software.

2. PV FED HIGH-GAIN DC-DC CONVERTER

2.1 High-gain DC-DC Converter

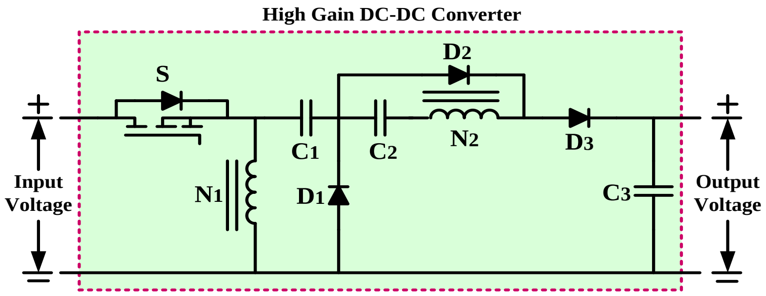
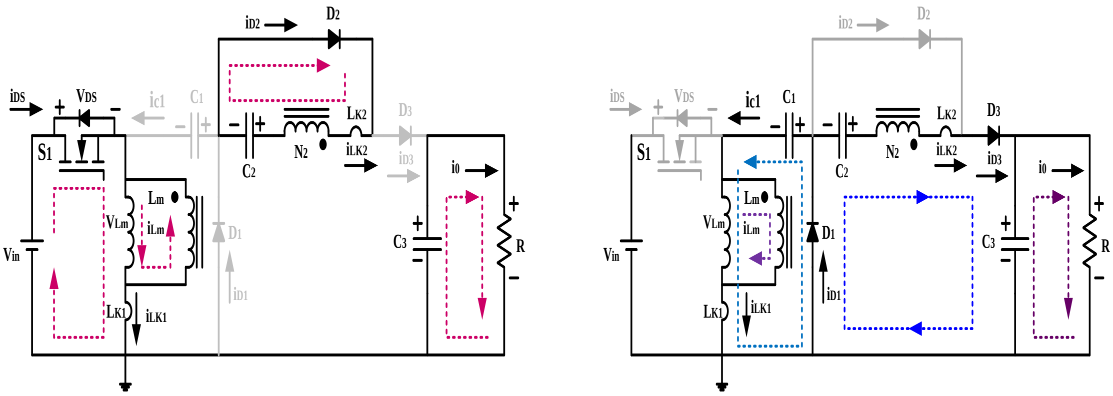


Figure 3. High gain dc-dc converter

The circuit configuration of high-gain DC-DC isolated converter is shown in Figure 3. The low voltage DC from PV system is fed to isolated DC-DC converter to boost the level of voltage.



(a) (b)

Figure 4. (a) High gain DC-DC converter when switch in ON, (b) switch in OFF

When switch S is in ON position, the primary inductor gets charged by input voltage through switch S1. At the same time the secondary inductor starts discharging and causes to charging the capacitor C2. In this case, capacitor C3 discharges and supplies to load at the output as shown in Figure 4(a).When switch S is in OFF position, then the charged primary inductor discharges through diode D1 and capacitor C1. Therefore capacitor C1 gets charges. Mean while the charged capacitor C2 starts discharging and causes to charge the secondary inductor and output capacitor C3 as shown in Figure 4(b). To simplify the steady-state analysis, only modes pertaining to switch OFF is considered for CCM operation, and the leakage inductance on the secondary and primary sides are neglected. By considering the average voltage across inductor and equating to zero during ON time and OFF time, the voltage gain for the high gain DC-DC converter is derived to be as (1), where ‘n’ is turns ration between primary to secondary of coupled inductor.

2.2. Closed-loop operation of High-Gain DC-DC Converter

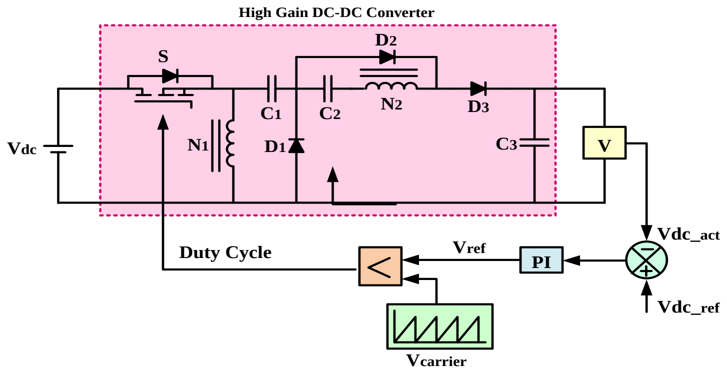


Figure 5. Closed-loop operation of high-gain DC-DC converter

Figure 5 shows the closed-loop mode of operation of high-gain DC-DC converter. The output voltage is fed back through a controller in closed-loop operation to obtain stable and constant DC output from high-gain converter. The actual output voltage is sensed across output capacitor of high-gain 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 to produce pulses to switch in high-gain DC-DC converter. This mode of operation yields a constant output with very less ripple.

The output of PV system is low voltage and it should be stepped-up to a certain voltage required by the system according to its configuration. The PV system connected to high-gain DC-DC converter is shown in Figure 6. A photovoltaic system, also PV system or solar power system is a power system designed to supply usable solar power by means of photo-voltaic. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity. Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere. Photovoltaic devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts. Hence they are used for power source, water pumping, remote buildings, solar home systems, communications, satellites and space vehicles, reverse osmosis plants, and for even megawatt scale power plants.

2.3 PV fed high-gain DC-DC converter

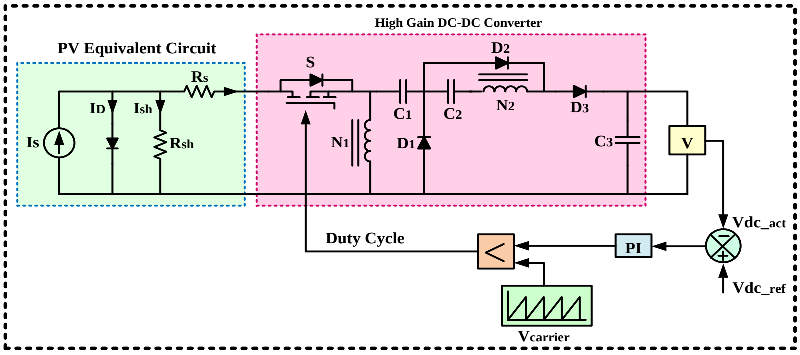


Figure 6. PV fed High gain DC-DC Converter configuration

The output of PV system is low voltage and it should be stepped-up to a certain voltage required by the system according to its configuration. The PV system connected to high-gain DC-DC converter is shown in Figure 6. A photovoltaic system, also PV system or solar power system is a power system designed to supply usable solar power by means of photo-voltaic. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity. Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere. Photovoltaic devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts. Hence they are used for power source, water pumping, remote buildings, solar home systems, communications, satellites and space vehicles, reverse osmosis plants, and for even megawatt scale power plants.

3. SINGLE CURRENT SENSOR BLDC MOTOR DRIVE

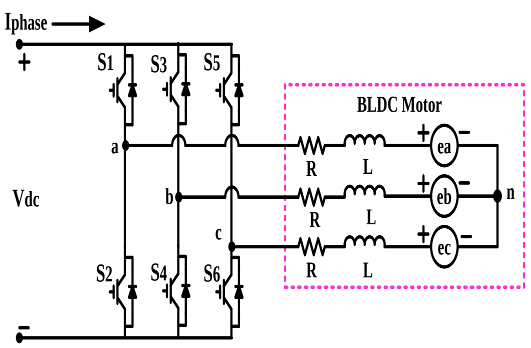


Figure 7. Converter fed BLDC motor

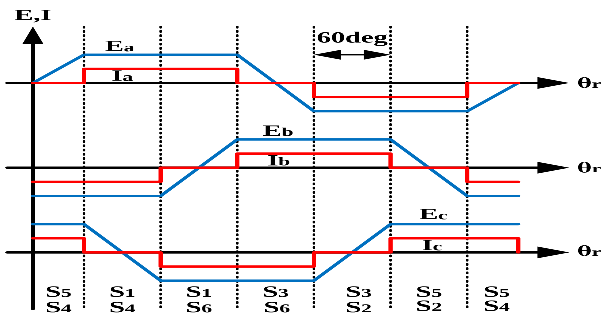


Figure 8. Back EMF in BLDC motor and phase currents

BLDC motor is excited from converter of BLDC motor which is typically a DC/AC converter. Typical converter fed BLDC motor is illustrated in Figure 7. The turn ON and OFF of power switches in inverter produces excitation for phase windings of stator coils in BLDC motor. The corresponding back EMF in BLDC motor and phase currents are shown in Figure 8.

In a BLDC motor two stator phases are energized at a time. Switching two switches of the inverter conducts switch (one upper and one lower of different legs) at any instant. Since two phases of the motor are energized at any instant and the motor is star connected, the same current flows through them. Also this current is same as the DC link current, measured by the single DC link current sensor. From the DC link current, the phase currents are estimated according to the phase current waveforms in Figure 8.

Speed control of BLDC motor in closed loop mode of operation is done with initial sensing of currents in stator of BLDC motor. Phase currents in stator windings are measured using current sensors. Sensors used for current sensing are of high cost and are heavy and becomes bulky. Also the use of different current sensors can cause undesirable imbalance in phase currents as well as torque fluctuations due to differences in current sensor sensitivities. These drawbacks can be avoided by using a single current sensor placed on the DC link. Table 1 represents the Rotor position and phase reference currents.

Table 1. Rotor position and phase reference currents

Rotor position (θ_e)	i_{aref}	i_{bref}	i_{cref}
0 – 30 deg	0	$-i_{ref}$	i_{ref}
30 – 90 deg	i_{ref}	$-i_{ref}$	0
90 – 150 deg	i_{ref}	0	$-i_{ref}$
150 – 210 deg	0	i_{ref}	$-i_{ref}$
210 – 270 deg	$-i_{ref}$	i_{ref}	0
270 – 330 deg	$-i_{ref}$	0	i_{ref}
330 – 360 deg	0	$-i_{ref}$	i_{ref}

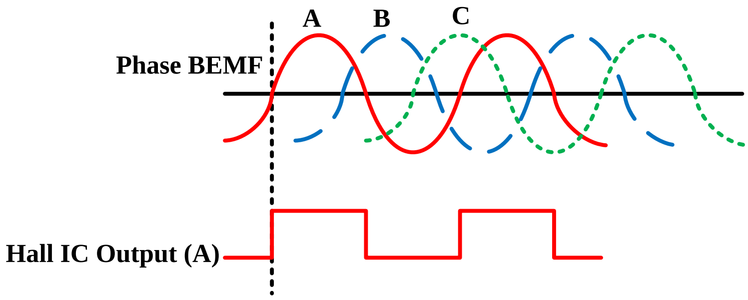


Figure 9. Phase relation between phase back EMF and hall output with single sensor

For closed-loop current control of brushless DC motors, instantaneous phase currents are measured using current sensors. Such sensors are often bulky, heavy, and expensive. In single DC link current sensor technique a single current sensor is placed in the DC link. From the measured DC link current, the phase currents can be estimated. Figure 9 illustrates phase relation between phase back EMF and hall output with single sensor

4. SPEED CONTROL OF CURRENT CONTROLLED BLDC MOTOR

The drive control system consists of an outer speed loop for speed control and an inner current loop for current control. Conventionally three separate current sensors are used to measure the phase currents. But here only one current sensor is used, which is placed on the DC link.

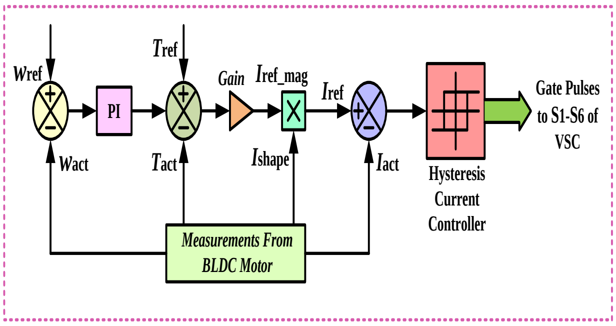


Figure 10. Current controlled BLDC motor speed control strategy

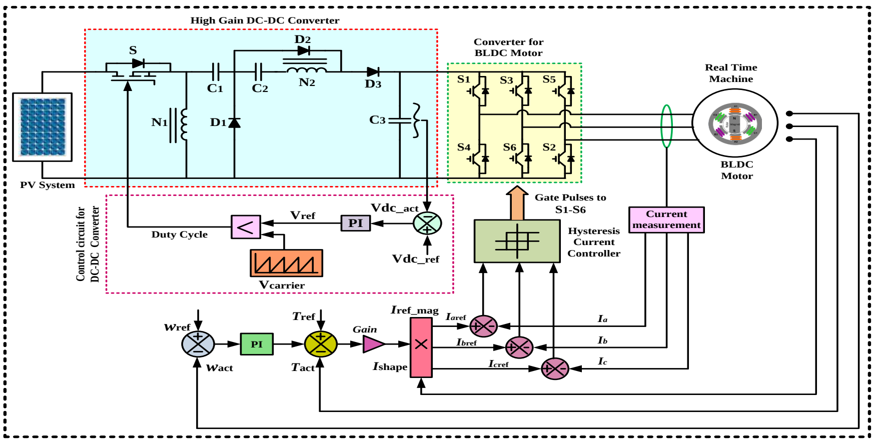


Figure 11. System configuration with current controlled BLDC motor drive supplied with PV fed high voltage gain DC-DC converter

Figure 10 shows the speed control strategy of BLDC motor with internal current controller. Primarily, the actual speed of BLDC motor is sensed from hall sensors and is compared to reference speed signal. The error generated from actual and reference speed is fed to a simple PI controller which yields reference torque signal. A PI controller attempts to correct the error between a measured process variable and desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. The obtained reference torque signal is compared with actual torque of BLDC motor and the error is fed through a gain to obtain reference current magnitude, as the current is proportional to torque signal. The obtained current magnitude and the current shape are multiplied to obtain reference current signal. The reference current signal is again compared to actual currents in stator of BLDC motor and the error is fed to hysteresis current controller to produce gate pulses to switches of voltage source converter (VSI). Thus by controlling the current of BLDC motor the speed control is achieved and motor is made to run at desired speed. The overall system with internal current controlled BLDC motor drive supplied with PV fed high voltage gain DC-DC converter is shown in Figure 11. Table 2 shows system parameters for simulation of the proposed system.

Table 2. System Parameters for simulation of the system

Parameters	Value
PV output voltage	40 V
Capacitor C1, C2 of DC-DC converter	47 µF
Capacitor C3 of DC-DC converter	1000

5. RESULTS AND ANALYSIS

5.1. Single current sensor BLDC motor drive operating with variable increamental speed and fixed torque

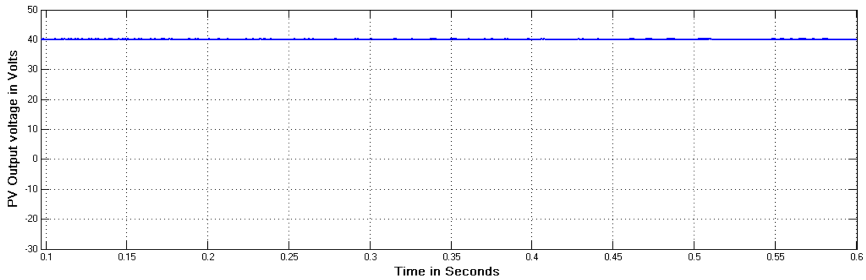


Figure 12. PV output in volts

The output voltage from photo-voltaic system with single current sensor BLDC motor drive operating with variable increamental speed and fixed torque is shown in Figure 12. PV yields the output of 40V as shown in Figure 12.

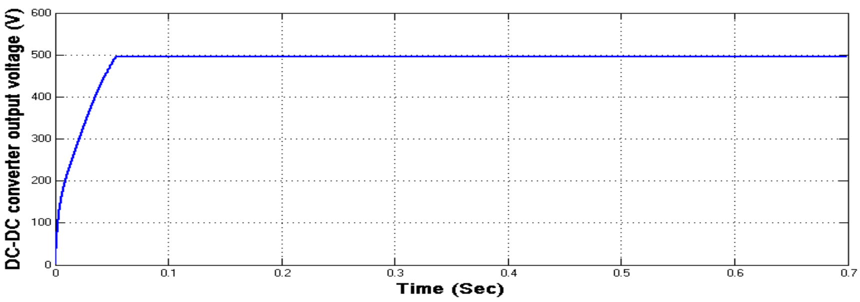


Figure 13. High-gain DC-DC converter output in volts

The output voltage from high gain DC-DC converter is shown in Figure 13. DC-DC converter increases the level of PV voltage from 40 V and gives out the output of 500V as shown in Figure 13. Even with speed change command, the output of DC-DC converter is maintained constant.

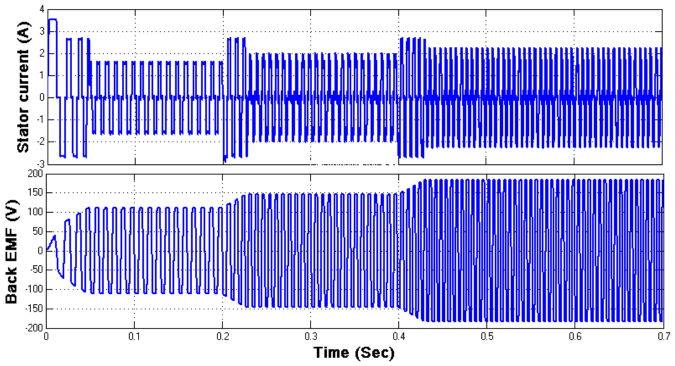


Figure 14. Stator currents and back EMF of BLDC motor

Stator current of one phase of BLDC motor and back EMF are shown in Figure 14. Since variable speed command is given at 0.2 sec and 0.4 sec, back EMF increase respectively with increase in speed. But the stator current drawn by the BLDC motor remains same with constant magnitude apart from slight disturbance at the time of change in speed.

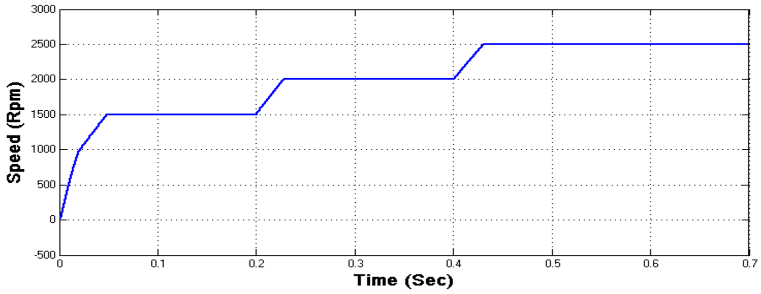


Figure 15. Speed of BLDC motor

Speed of BLDC motor is shown in Figure 15. Since the variable speed condition is applied, the speed changes at 0.2 sec and 0.4 sec. Incremental speed command is given at 0.2 sec and at 0.4 sec to be initially at 1500rpm with change to 2000 rpm at 0.2 sec and 2500 rpm at 0.4 sec respectively and the actual speed follows the set speed command.

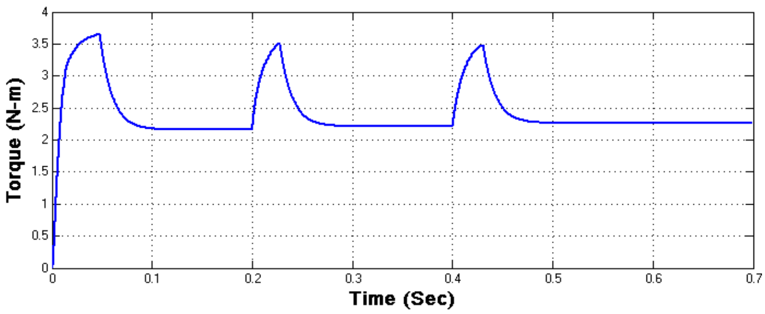


Figure 16. Torque of BLDC motor

Torque of BLDC motor is shown in Figure 16. Since the variable speed condition is applied, the change of torque is at 0.2 sec and 0.4 sec with respective speed change command but settles soon to final value. Even though, the speed changes, torque remains constant apart from fluctuations.

5.2 Single current sensor BLDC motor drive operating with variable decreamental speed and fixed torque

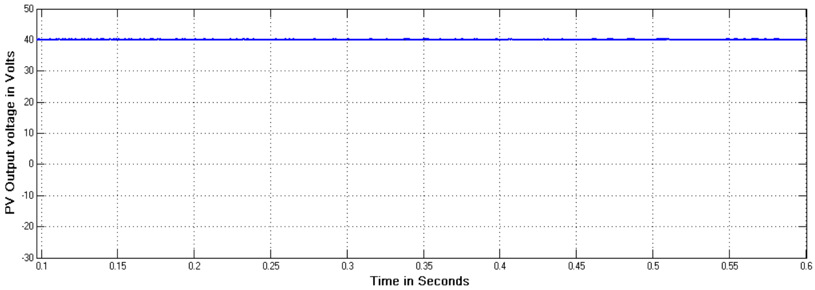


Figure 17. PV output in volts

The output voltage from photo-voltaic system with single current sensor BLDC motor drive operating with variable decreamental speed and fixed torque is shown in Figure 17. PV yields the output of 40V as shown in Figure 17.

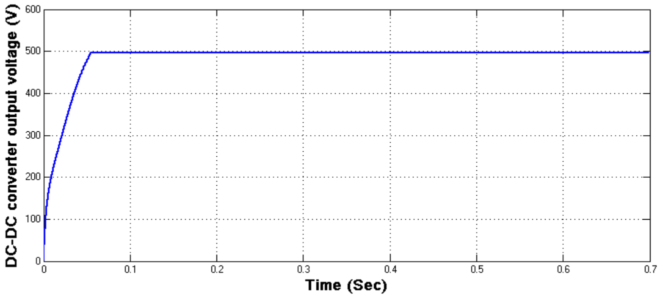


Figure 18. High-gain DC-DC converter output in volts

The output voltage from high gain DC-DC converter is shown in Figure 18. DC-DC converter increases the level of PV voltage from 40 V and gives out the output of 400V as shown in Figure. Even with speed change command, the output of DC-DC converter is maintained constant.

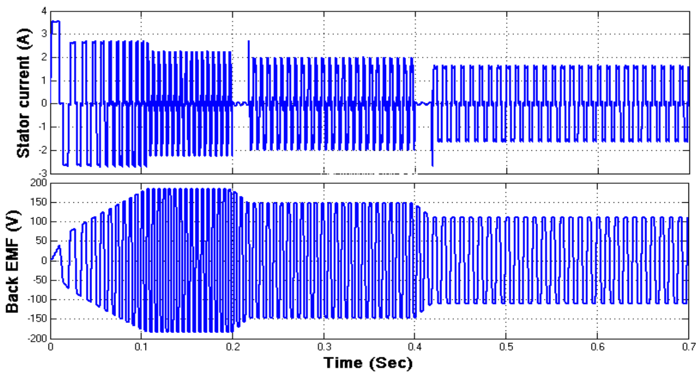


Figure 19: Stator currents and back EMF of BLDC motor

Stator current of one phase of BLDC motor and back EMF are shown in Figure 19. Since variable speed command is given at 0.2 sec and 0.4 sec, back EMF decrease respectively with decrease in speed. But the stator current drawn by the BLDC motor remains same with constant magnitude apart from slight disturbance at the time of change in speed.

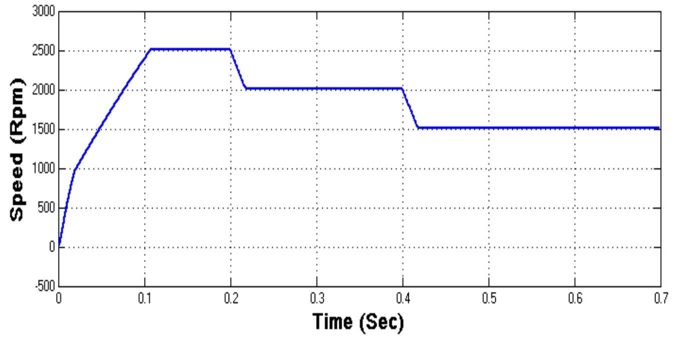


Figure 20: Speed of BLDC motor

Speed of BLDC motor is shown in Figure 20. Since the variable speed condition is applied, the speed changes at 0.2 sec and 0.4 sec. Decremental speed command is given at 0.2 sec and at 0.4 sec to be initially at 2500rpm with change to 2000 rpm at 0.2 sec and 1500 rpm at 0.4 sec respectively and the actual speed follows the set speed command.

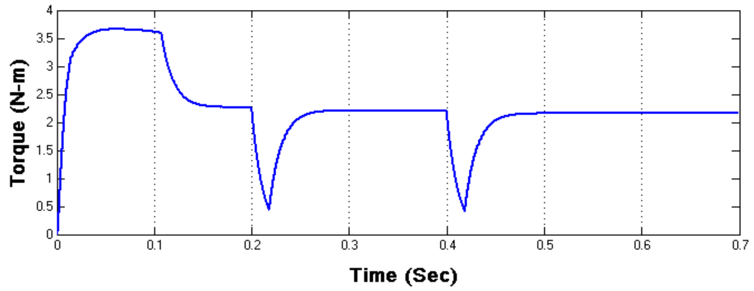


Figure 21: Torque of BLDC motor

Torque of BLDC motor is shown in Figure 21. Since the variable speed condition is applied, the change of torque is at 0.2 sec and 0.4 sec with respective speed change command but settles soon to final value. Even though, the speed changes, torque remains constant apart from fluctuations.

5.3 Single current sensor BLDC motor drive operating with variable torque and fixed speed

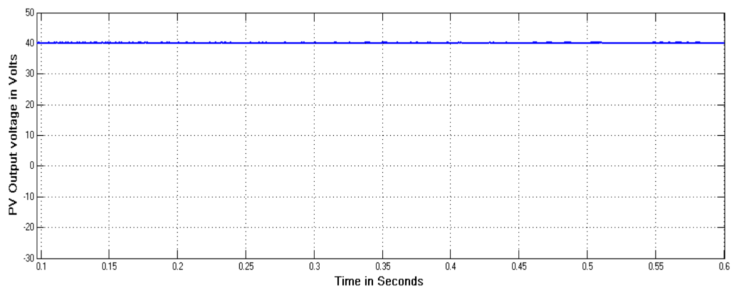


Figure 22: PV output in volts

The output voltage from photo-voltaic system with single current sensor BLDC motor drive operating with variable torque and fixed speed is shown in Figure 22. PV yields the output of 40V as shown in Figure.

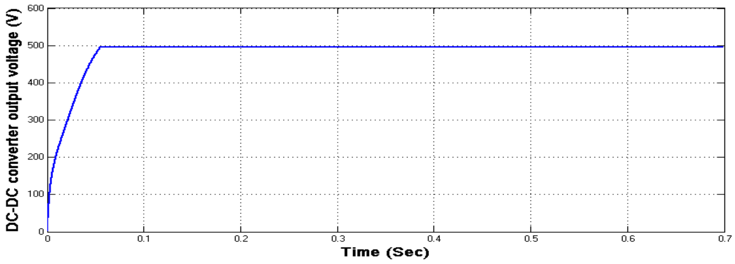


Figure 23: High-gain DC-DC converter output in volts

The output voltage from high gain DC-DC converter is shown in Figure 23. DC-DC converter increases the level of PV voltage from 40 V and gives out the output of 500V as shown in Figure. Even with torque change command, the output of DC-DC converter is maintained constant.

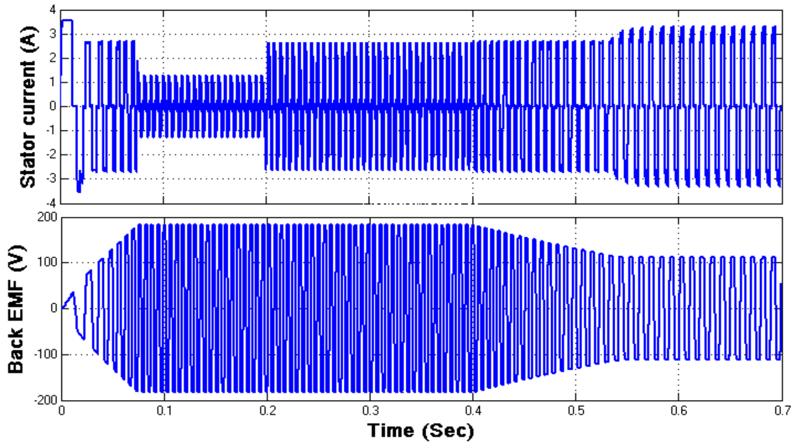


Figure 24: Stator currents and back EMF of BLDC motor

Stator current of one phase of BLDC motor and back EMF are shown in Figure 24. Since variable torque command is given, back EMF decrease respectively with increase in stator current.

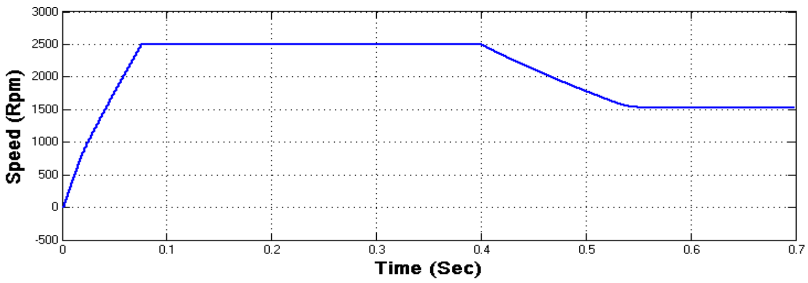


Figure 25: Speed of BLDC motor

Speed of BLDC motor is shown in Figure 25. Since the variable torque command is given at 0.2 sec and 0.4 sec, the speed remains constant at respective changes of 0.2 sec. But when torque still increases at 0.4 sec, the speed decreases and remains constant.

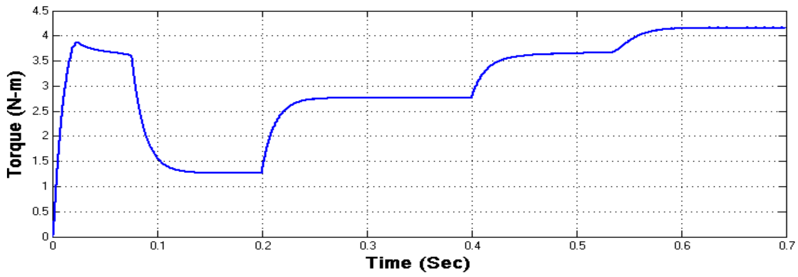


Figure 26: Torque of BLDC motor

Torque of BLDC motor is shown in Figure 26. Since the variable torque condition is applied, the change of torque is at 0.2 sec and 0.4 sec is observed from Figure 26.

6. CONCLUSION

This paper presents the performance of Brushless DC (BLDC) Motor drive with only one positioning sensor instead of three conventional sensors. The three sensor units are replaced with a single stator current sensor unit in DC bus which further reduces the cost increasing the reliability of the drive system. A high voltage-gain DC-DC converter is presented in this paper to step-up the voltage from PV system. The appropriateness of PV fed BLDC motor drive is verified for variable increamental speed with fixed torque and variable decremental speed with fixed torque operating conditions. BLDC motor drive performance is also performed for variable torque with fixed peed working condition. BLDC motor operates satisfactorily with dynamic conditions using only one current sensor.

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