



An Integrated Single-Stage Converter fed Sensor-less Motor Drive

V. Aishwarya, K. Gnana Sheela

Abstract: This paper details an Integrated Single-stage converter fed sensor-less BLDC motor drive. The drive speed is regulated by altering the DC voltage of the inverter that drives the motor. The switches of the inverter are operated at the line frequency, thereby reducing the inverter switching stresses and enhancing the overall drive system efficiency. The converter works in Dual-discontinuous Current Mode (D-DCM) for Power Factor Correction (PFC) and better power quality at the supply mains. DC voltage control is used adjust the duty ratio of the converter switch. Fast voltage regulation, zero current switching at turn-on and enhanced power factor for a broad range of speeds are the advantages of this converter configuration. The necessity of Hall-Effect position sensors is eliminated by employing a sensor-less technique for brushless dc motor commutation. This reduces the dimensions, volume and expenditure of the motor drive and upgrades its overall efficiency. Drive performance is assessed over an extensive span of speeds. A power factor approximating to unity, and enhanced power quality indicators which are adequately within the sanctioned cap of IEC standard 61000-3-2 are obtained.

Index Terms: BLDC motor, Integrated Single-Stage Converter, Voltage Source Inverter, Digital Commutation, Voltage Mode Control, Dual-Discontinuous Conduction Mode

I. INTRODUCTION

Sensor-less BLDC motor drives are largely employed in low-power, low-cost applications owing to features like faster dynamic response, high ruggedness, high power density, extended running life, enhanced efficiency, silent operation, exalted torque-to-weight ratio, broader speed ranges [1,2]. These motors have no brushes in them, and current commutation in the windings is implemented electronically based on feedback of the rotor position. Thus, they include sensors to detect the exact rotor position. This escalates the price and motor dimensions and minimizes its sturdiness [2]. Economization of variable-frequency drives is possible through two methods, which includes topological method and control method. The first approach aims at minimalistic utilization of switches in the power circuit whereas, the later approach aims at designing & implementing new control strategies for securing the desired dynamics [2,3].

Thus, several sensor-less control techniques for enhancing the performance of these drives like Back-EMF zero-crossing detection, Varying inductance approach, Flux-linkage variation, MRAS control, Extended Kalman Filter method etc. have been described in [2,4-9].

Compared to multi-stage drives, an Integrated Buck-boost Buck converter is a single-stage converter employing a single switch, which offers advantages like reduced switching losses, improved dynamic performance, power factor correction, improved power quality, fast voltage regulation, and Zero-Current switching(ZCS) at Turn-ON for reduced losses at the switch[1].The PFC converters generally have two operational modes: (i) Continuous Conduction Mode (CCM) (ii) Discontinuous Conduction Mode (DCM). CCM offers continuous current through the inductor, reduced stress on the converter switch, at a higher sensor count [20]. This mode is generally employed in large power applications. DCM offers discontinuous inductor current and demands a unit sensor for sensing the voltage of the DC-bus [25]. Here, the switching stress rises, and is restrained to lower power appliances [16-20].The losses in the inverter switches during conduction are minimized by triggering the inverter switches at the line frequency for commutating the motor. The converter functions in the Dual-discontinuous Conduction Mode (D-DCM) [18]. This necessitates a unit sensor for both control of speed and PFC at the AC supply mains [26]. Drive speed is regulated by employing Voltage Mode Control. Sensor-less control is realized using Direct Back-EMF Zero crossing detection technique [24]. This work investigates the various analyses of the Integrated Single-stage converter fed Sensor-less motor drive.

II. SYSTEM CONFIGURATION

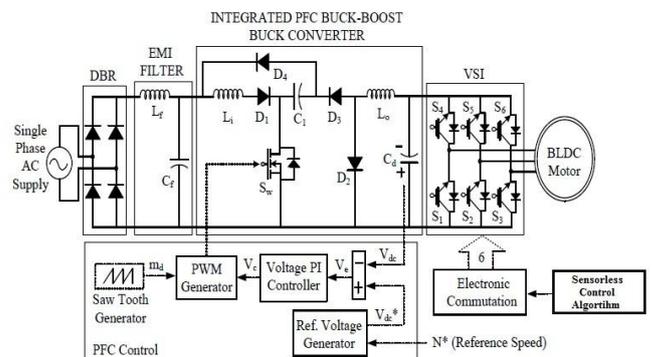


Fig.1. Integrated single-stage converter fed motor drive
The drive incorporates a power circuitry, BLDC motor and a controlling unit. The power circuitry is constructed using a full-bridge diode-rectifier, an EMI filter and the Integrated single-stage converter.

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This Integrated converter is a combination of a simple Buck-boost converter and a Buck converter [1]. This converter is cascaded to the output of a rectifier to yield a controlled dc output voltage as seen in Fig. 1 [2].

A low-pass filter following the bridge rectifier eliminates the ripples and EMI issues. Voltage Mode Control is utilized for converter control. Voltage control and power factor correction are obtained by working the converter in D-DCM. The inverter switches are triggered at the line frequency for accomplishing commutation of the motor digitally, and help in the minimization of switching losses and improved efficiency of the VSI [18]. Sensor-less Direct Back-EMF Zero-Crossing detection technique has been used for the digital commutation of the motor [18, 24]. Here, the triggering patterns are developed from three Back-EMFs of the motor phases. This control scheme does not require any sensor to identify the rotor position each 60 electrical degrees & thus helps in cost-reduction of the drive system [17].

III. OPERATION OF THE CONVERTER

This section explains the working of the converter in D-DCM. It operates in a manner that the current in the input inductor, L_i and output inductor, L_o become discontinuous in a switching period [27]. Figs. 2(a)-(d) show the four modes of the converter in one cycle of switching and, Fig. 2(e) illustrates the related waveforms [1,17]. **Mode I:** When the switch S_w is triggered ON, the input inductor L_i starts charging through the switch and diode D_1 [17]. The current i_{L_i} increases, with the rate of increase depending upon the instantaneous voltage applied. Capacitor C_1 charges via the switch, L_o , & diode D_3 to charge the coupling capacitor C_d as in Fig. 2(a). Diodes D_2 and D_4 remain reverse biased in this mode. In this mode, Currents i_{L_i} and i_{L_o} increase while voltage V_{C_1} decreases [18]. **Mode II:** When switch, S_w is switched OFF, inductors, L_i and L_o discharges to charge the capacitors C_1 and C_d as seen in Fig. 2(b). D_3 remains reverse biased, while D_1 , D_2 and D_4 conduct for achieving a closed loop for energy transfer between the inductors and capacitors [1]. V_{C_1} starts increasing till the reserved energy in the input inductor, L_i becomes zero. Finally, i_{L_i} reaches zero and enters the DCM mode, while still some energy is left in L_o due to its higher value of time constant, as in Fig. 2(e) [1]. **Mode III:** Switch S_w stays in OFF state. The source does not supply any energy to the converter in this mode. L_o supplies all of its energy to charge C_d as in Fig. 2(c). Hence, V_{dc} continues to increase. V_{C_1} remains constant in this mode. Finally, L_o is completely discharged and i_{L_o} becomes zero. **Mode IV:** In this operational mode, no energy remains in the input inductor, L_i and output inductor L_o . Hence, the converter goes into dual DCM operation as in Fig. 2(d) and Fig. 2(e). Coupling capacitor, C_d contributes the sufficient energy required to the load and V_{dc} decreases [17]. Capacitor C_1 remains charged with the highest possible voltage. This mode is completed at this juncture of the switching state, and the complete cycle is repeated for the next switching state.

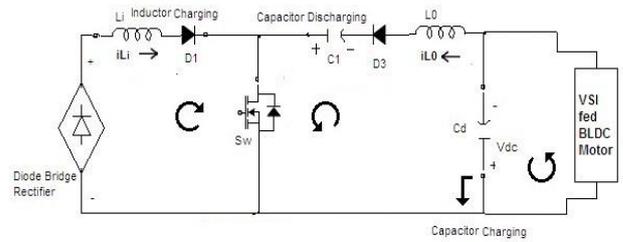


Fig 2a. Mode I

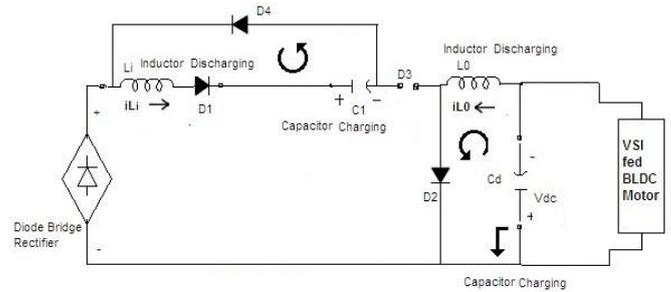


Fig 2b. Mode II

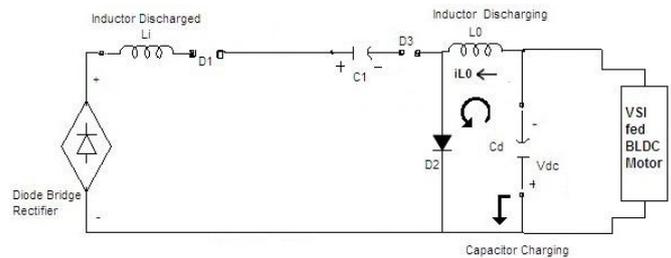


Fig 2c. Mode III

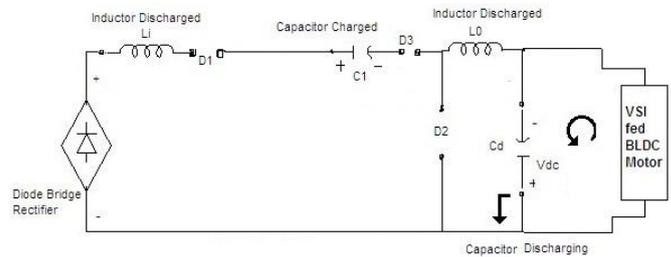


Fig 2d. Mode IV

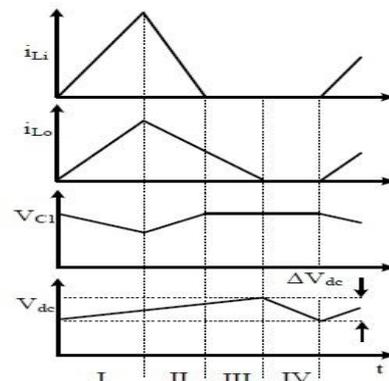


Fig 2e. Waveforms of the converter in D-DCM [1].

IV. SYSTEM CONTROL

System Control can be divided into two parts: (i) Converter control to obtain voltage control & power factor correction. (ii) Digital commutation of motor [1, 20-23].

A. Converter Control

In this approach of voltage control, a reference voltage (V_{dc}^*) proportional to a desired speed (N^*) is generated by multiplying the desired speed reference with the motor back-EMF constant [21, 22].

$$V_{dc}^* = k_v N^* \quad (1)$$

Where, k_v represents motor voltage constant, N^* denotes the desired speed. This proportional voltage is matched with the exact DC voltage to create a voltage error, V_e [21, 22]. Voltage error at a discrete time, ' t ' is given by:

$$V_e(t) = V_{dc}^*(t) - V_{dc}(t) \quad (2)$$

This voltage error is given to a digital controller to develop a digitally-regulated output voltage, V_d as [17, 21, 22]:

$$V_d(t) = V_e(t-1) + k_p \{V_e(t) - V_e(t-1)\} + k_i V_e(t) \quad (3)$$

where, k_p and k_i represent the proportional & integral gain constants respectively. At last, the voltage, V_d is modulated using a high frequency carrier waveform to develop gating pulse for the converter switch as:

$$m_d(t) < V_d(t), \text{ then } S_w = 1; \text{ else } S_w = 0 \quad (4)$$

where, S_w denotes the switching pulse for the converter.

B. Digital commutation of motor

In the conventional sensed control technique, Sensors are needed to identify the rotor's angular position during every 60° electrical, so as to perform the current commutation of each phase efficiently. These sensors escalate the volume, weight & price, and decrease the total drive efficiency & reliability. Here, a sensor-less control strategy is employed, that minimizes the overall bulkiness, volume and price of the drive system. A zero crossing detector (ZCD) is used to sense the instant each time the EMF in the un-energized phase passes through zero [10-13]. At this juncture, the back-EMF can be measured, and it crosses zero [12]. Now, the corresponding phase voltage is equal to the neutral voltage. This point is phase-shifted by 30° electrical to yield the switching pattern [11-13, 21, 24].

V. RESULTS AND DISCUSSION

The drive performance is assessed for several speeds, source voltages and torques on the motor [17]. Motor parameters such as rotor speed (ω_m), motor torque (T_e), stator current (i_a), back-EMF (E_b) are observed. Converter parameters like DC voltage, inductor currents, and intermediate capacitor voltages are studied to demonstrate the performance of the front-end converter [3, 17]. Power quality indicators like power factor (PF) & source current harmonic distortion (THD) are assessed. Peak voltage stress and peak current stress of the converter switch is measured [1, 20, 22, 23].

A. Steady State Behaviour of the drive

Fig. 3 illustrates the performance characteristics of the drive at rated conditions during steady state operation. The supply current in phase-coincidence with the source voltage confirms a power factor of one. Discontinuity in both the inductor currents and continuous conduction of intermediate capacitor voltage demonstrates the converter operation in D-DCM. Current and voltage stresses in the converter switch is obtained as 22A and 800V respectively, and are found to be within the acceptable range. A power factor of 0.99 and THD < 5% is achieved for a wide range of speeds and is found to be within the acceptable limits if IEC61000-3-2.

Fig.4. shows that a Zero Current Switch (ZCS) turn-on phenomenon is obtained, as V_{sw} becomes zero during the turn-on of the converter switch. Hence, the losses in the converter are minimized during switching.

C. Performance during Supply Voltage Fluctuation

Fig. 5 illustrates the dynamic behaviour of the drive during a fluctuation of source voltage from 270V to 180 V. This demonstrates the behaviour of the drive during practical supply voltage variations.

D. Dynamic Performance of the drive

Three conditions have been studied so as to understand the behaviour of the drive to the following rapid variations: (i) starting of the drive with increase in dc voltage from 0V to 75V (ii) dynamic behavior at speed control with a step-rise in dc voltage from 100V to 150V (iii) Dynamic behaviour of the drive at a step-rise in torque from 0.4Nm to 0.8Nm. Fig. 6 illustrates the dynamic behaviour at starting with a step-rise in the dc voltage from 0V to 75V; Fig. 7 demonstrates the dynamic behaviour at speed control with a step-rise in the dc voltage from 100V to 150V; Fig. 8 illustrates the dynamic characteristics at a step-increase in load torque from 0.4Nm to 0.8Nm. A power factor closer to one, and a source current THD < 5% are obtained. As the dc voltage, V_{dc} is regulated evenly in the entire working range; a sound performance is achieved in this drive.

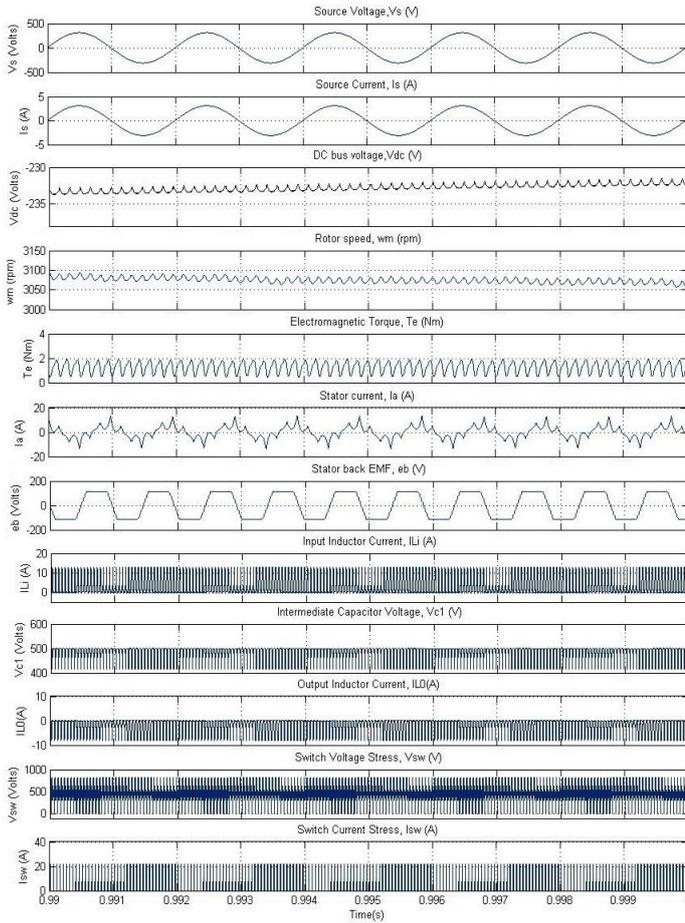


Fig. 3. Steady state behaviour of the drive

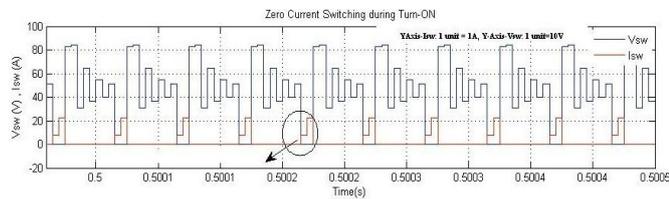


Fig. 4. Zero Current Switching during turn-on

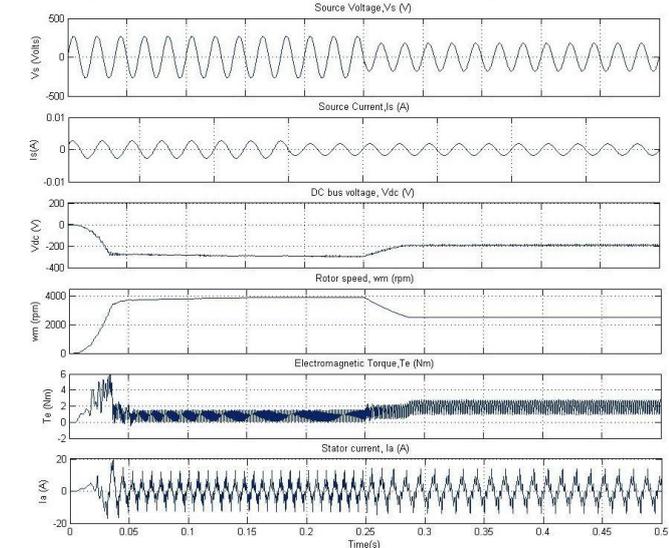


Fig. 5. Dynamic characteristics for a step-fall in supply voltage from $V_s=270V$ to $180V$

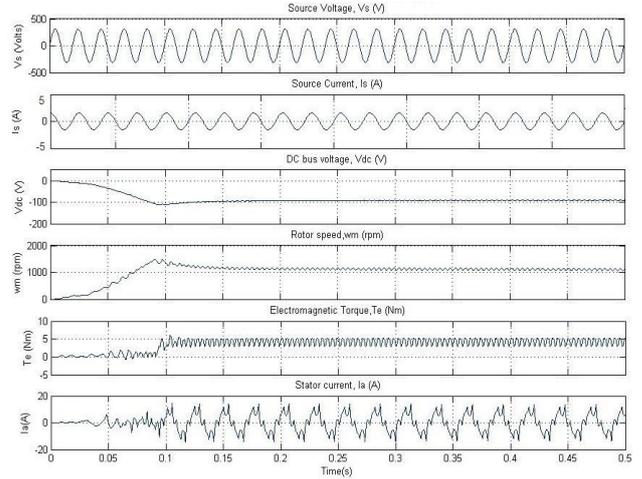


Fig. 6. Dynamic characteristics at Start Up from $V_{dc} = 0V$ to $75V$

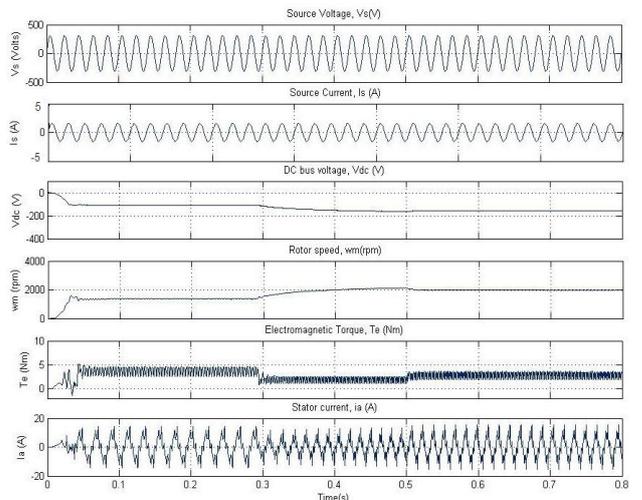


Fig.7. Dynamic characteristics for a step-rise in dc-link voltage from $V_{dc} = 100V$ to $150V$.

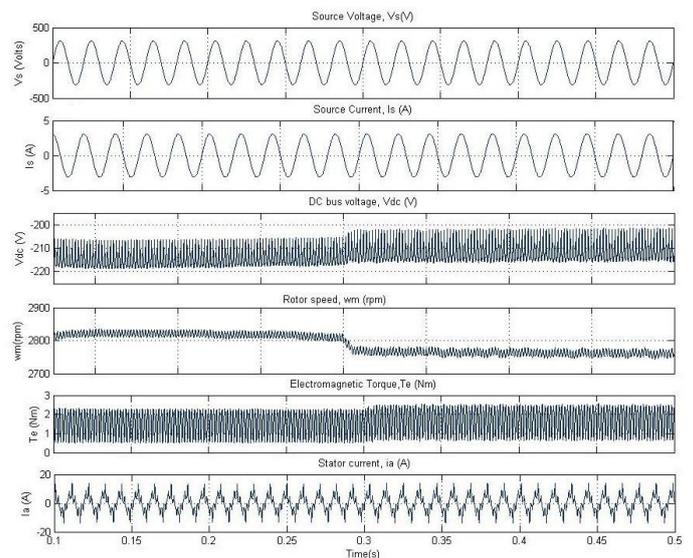


Fig. 8. Dynamic characteristics for a step-rise in torque from $0.4Nm$ to $0.8Nm$

VI. CONCLUSION

The performance evaluation of an Integrated, Single-stage converter-fed motor drive is introduced in this paper. Variable dc voltage method is employed for the drive speed control. Solid-state switches of the VSI are operated at the line frequency employing digital current commutation, thus minimizing their switching losses. Sensor-less Direct Back-EMF Zero-Crossing Detection scheme is utilized in developing the triggering pattern for the VSI switches. Overall efficiency of the drive is improved considerably due to reduction in the number of sensors, switching of the VSI switches at the fundamental frequency and Zero current turn-on of the converter switch. An inherent power factor correction and DC voltage control are achieved as the converter operates in D-DCM. The drive is analyzed for a comprehensive set of speeds and supply voltage variation and the PQ indices obtained are found to be inside the suggested ceilings of IEC 61000-3-2. This drive is recommended for use in low-power applications requiring vast speed control and uplifted power quality.

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