NOVEL CONTROL STRATEGY FOR BRIDGELESS BOOST CONVERTER FED PMBLDC MOTOR

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Abstract : This paper proposes a novel Bridgeless converter to drive and speed control of PMBLDC motor. PMBLDC motor possess high torque/weight ratio, operate at high speed, very compact and are electronically controlled. The speed control of BLDC motor is achieved by controlling the DC link voltage of the voltage source inverter feeding BLDC motor using a single voltage sensor. Conventional bridged topology is replaced by bridgeless topology. Conventional PMBLDCM drive consists of a VSI and a PMBLDC motor powered by a diode bridge rectifier, fed by single-phase AC mains and a smoothening DC capacitor. Due mainly to uncontrolled charging of the DC capacitor at the input AC mains, there will be resultant problems, such as a poor power factor, and increased THD of current. Therefore, it has become necessary to design a suitable passive filter to reduce THD, and improve the power factor of a PMBLDC motor drive. Performance at various operating conditions such as starting, dynamic and steady state behavior are analyzed and suitability of the proposed system is demonstrated using MATLAB/Simulink based simulation results.

***IndexTerms* - AC–DC power conversion, MOSFET-based rectifier, PWM, PMBLDC motor drive.**

I. INTRODUCTION

PMBLDC motors are widely used for high-speed drive applications due to their high power density and high efficiency and compact solution for the motion of equipment in the range from fraction to a few kilowatts because the methods to control their speed are simple and precise [1],[2]. In addition to these advantages, PMBLDC motors have more power density and the complexity of the position sensors of PM BLDC motors is very low [3]. It is electrically commutated by power switches instead of brushes. Compared with a brushed DC motor or an induction motor, the BLDC motor has many advantages such as higher efficiency and reliability, lower acoustic noise, compact, robust and high power density

This paper proposes a high-efficiency bridgeless three-level PFC rectifier. The proposed rectifier minimizes the overall power losses by eliminating the full-bridge diode rectifier and the reverse recovery problems of the MOSFET body diodes. Also, the proposed rectifier reduces the power losses, harmonic components, voltage ratings. The various performances are analyzed through the simulated results using MATLAB/Simulink environment.

II. DETAILS OF THREE-PHASE PMBLDC MOTOR

The proposed PMBLDC drive includes a single phase source, a diode bridge rectifier (DBR), a canonical switching based bridgeless boost converter controlled using a novel PFC based speed control scheme for PMBLDC drive, a three phase VSC bridge and a PMBLDC motor. The DBR converts the AC into rectified DC. The proposed control scheme operates the boost converter in such a manner that the current drawn by the DBR from the source is always remains sinusoidal and in-phase with the source voltage. Typical waveforms for a PMBLDC motor with trapezoidal back-EMF distribution are shown in fig.1. The back-EMF is constant for 120° flat shape; it changes linearly with rotor angle. So that, constant output power and constant output torque are maintained. Current is driven through a motor winding during the flat portion of the back-EMF waveform. The phase currents have to be synchronized with the corresponding phase back-EMF voltages to drive the motor with maximum and constant torque [2].

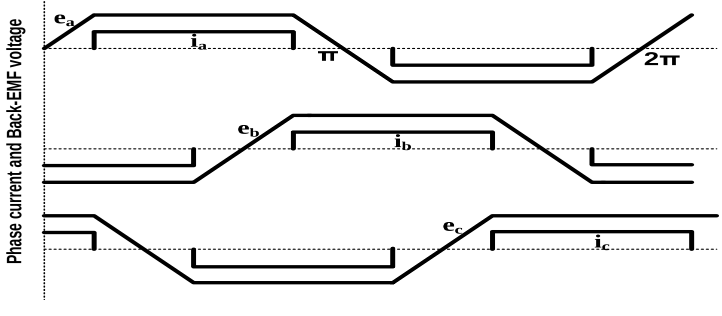

Fig. 1 Phase back-EMF and current waveforms of PMBLDC motor

III. OPERATION OF PROPOSED SYSTEM CONFIGURATION

The proposed control scheme consists of a voltage control loop only and operated using voltage follower approach with discontinuous mode (DCM) operation of the DC-DC converter. Fig. 2 shows the schematic of the proposed bridgeless converter based PMBLDCM drive operated with voltage follower control. The proposed controller is to maintain a DC link voltage (V_{dc}). The DC link voltage (V_{dc}) is sensed and compared with a reference voltage (V*dc) which results to generate voltage error. This voltage error is passed through a voltage controller to give the modulating current signal which is amplified and compared with saw-tooth carrier wave of fixed frequency (fs) to generate a pulse width modulated (PWM) signal for the switching device of the DC-DC converter.

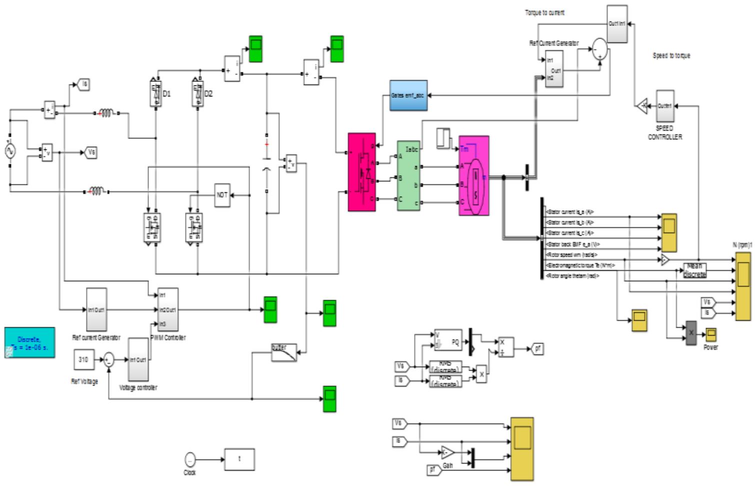

Fig. 2 Simulink model of proposed bridgeless boost converter-fed BLDC motor

For the speed control, the speed signal which is sensed from Hall effect sensors from rotor position of the PMBLDCM, is compared with a reference speed. The resultant speed error is passed through a speed controller to get the torque equivalent which is converted to an equivalent current signal using motor's torque constant. This current signal is multiplied with a rectangular unit template waveform which is in phase with top flat portion of motor's back EMF so that reference three-phase currents of the motor are generated. These reference currents are compared with the sensed motor currents and current errors are generated which is amplified and compared with triangular carrier waves to generate the PWM signals for the VSI switches.

IV. MODELING OF THE PROPOSED PMBLDCM DRIVE

The modeling of proposed PMBLDCM drive includes the designing of the PFC converter and PMBLDCM drive. The mathematical equations are given for its component modeling and the whole drive is demonstrated as a pairing of these models.

A. PFC Converter

The PFC converter involves a Bridge Rectifier at its front end and an output ripple filter with buck-boost converter. The PFC converter modeling includes the designing of a voltage controller and a Pulse Width Modulation controller as shown below.

B. Voltage Controller

The voltage controller is used for monitoring the voltage error. This is one kind of proportional-integral (PI) controller It helps in generating control signal (Ic) to reduce the voltage error. If at kth instant of time, $V^*_{dc}(x)$ is reference DC link voltage, $V_{dc}(x)$ senses DC link voltage then the voltage error $V_e(x)$ is calculated as given below,

$V_e(x)=V^*_{dc}(x)-V_{dc}(x)$ (1)

The output of the controller Ic(k) at kth instant is given as,

$I_c(x) = I_c(x-1) + K_{pv}\{V_e(x) – V_e(x-1)\} + K_{iv}V_e(x)$ (2)

where K_{pv} and K_{iv} are the proportional and integral gains of the voltage PI controller.

C. PWM Controller

The outcome of Proportional Integral controller is amplified by gain k_{dc} and a comparative analysis is done with fixed frequency (fs) saw-tooth carrier waveform md(t) for achieving the switching signals for the MOSFET of the proposed buck-boost PFC converter. This is shown in Fig. 3 and given as below,

If $k_{dc} I_c(x) > m_d(t)$ then S = 1 (3)

If $k_{dc} I_c(x) \leq m_d(t)$ then S = 0 (4)

where S is the switching function representing 'on' position of the MOSFET of the PFC converter with S=1 and its 'off' position with S=0.

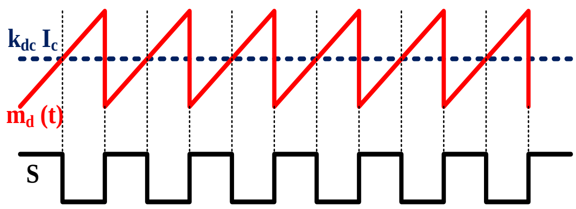

Fig. 3: PWM controller signals of proposed buck-boost PFC converter

E. PMBLDCM Drive

The PMBLDCM drive consists of a speed controller, a reference current generator, a PWM current controller, a voltage source inverter (VSI) and a PMBLDC motor as its important components. The speed controller is a kind of PI controller which helps in tracking the reference speed. If at kth instant of time, $\omega^*_r(k)$ is the reference speed, $\omega_r(k)$ is the rotor speed then the speed error $\omega_e(k)$ can be calculated as,

$\omega_e(x) =\omega_r^*(x)- \omega_r(x)$ (5)

For achieving the desirable control signal, this speed error is processed via the speed controller.

Speed controller

The speed controller's output at kth instant T(k) is given as,

$T(x) = T(x-1) + K_{p\omega}\{\omega_e(x) – \omega_e(x-1)\} + K_{i\omega}\, \omega_e(x)$ (6)

where $K_p\omega$ and $K_i\omega$ are the proportional and integral gains of the PI speed controller.

Reference Winding Current Generator

The magnitude of stator winding current is calculated as,

$I^* = T(x) / (2K_b)$ (7)

where, Kb is the back electromotive force constant of the PMBLDCM.

The reference phase currents of the PMBLDCM are represented by ia*, ib*, ic* for phases a, b, c respectively. The reference currents can be given for time duration of 0-60o, which is given below as,

$i^*_a = I^*$, $i^*_b = - I^*$ and $i^*_c = 0$ (8)

In the same way, the reference winding currents at another 60^o duration are created in rectangular 120^o block form which is in phase with trapezoidal voltage of respective phases. These reference currents are compared with sensed phase currents (i_a, i_b, i_c) for generating the current errors $\Delta i_a=(i_a^* - i_a)$, $\Delta i_b=(i_b^* - i_b)$, $\Delta i_c=(i_c^* - i_c)$ for 3-ϕ of the motor.

F. PWM Current Controller

The current errors Δi_a, Δi_b, Δi_c are amplified by gain k1 and compared with carrier waveform m(t) of a fixed frequency in the PWM current controller for generating the switching sequence for the voltage source inverter. The switching sequence is created based on the logic given for phase "a" as,

If $k1\ \Delta i_a > m(t)$ then Sa = 1 ('IGBT ON') (9)

If $k1\ \Delta i_a \le m(t)$ then Sa = 0 ('IGBT OFF') (10)

The switching sequences Sb and Sc are created by using same logic for other two phases of the motor.

Voltage Source Inverter

Fig. 4 shows an equivalent circuit of a Voltage Source Inverter fed to PMBLDCM. The outcome of VSI to be fed to phase 'a' of the PMBLDC motor is depicted as below,

$v_{ao} = (V_{dc}/2)$ for $S_a = 1$ (11)

$v_{ao} = (-V_{dc}/2)$ for $S_a = 0$ (12)

$v_{ao} = 0$ for $I^*a = 0$ (13)

$v_{an} = v_{ao} - v_{no}$ (14)

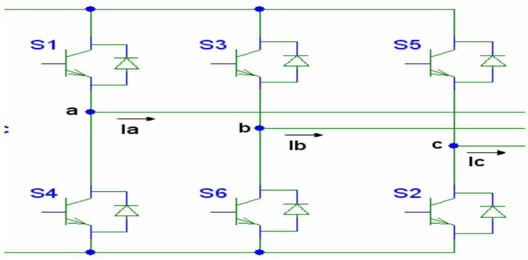

Fig.4 Equivalent Circuit of a VSI

where v_{ao}, v_{bo}, v_{co}, and v_{no} are voltages of 3-ϕ and neutral terminal (n) w.r.t virtual mid-point of the DC link shown as junction point in Fig. 4. By using the same concept vbo, vco, vbn, vcn are created for other 2-ϕ of the VSI feeding PMBLDC motor. The voltages van, vbn, and vcn are voltages of 3-ϕ w.r.t. the motor neutral terminal (n).

G. PMBLDC Motor

The PMBLDCM is presented in the form of a set of differential equations [7] given as below,

$v_{an} = Ri_a + p\lambda_a + e_{an}$ (15)

$v_{bn} = Ri_b + p\lambda_b + e_{bn}$ (16)

$v_{cn} = Ri_c + p\lambda_c + e_{cn}$ (17)

where p is a differential operator (d/dt), i_a, i_b, i_c are 3-ϕ currents, flux linkages are λ_a, λ_b, λ_c and ean, ebn, ecn are phase to neutral back emfs of PMBLDCM, in respective phases, R is denoted as the resistance of motor windings/phase.

The flux-linkages are presented as,

$\lambda_a = L_s i_a - M (i_b + i_c)$ (18)

$\lambda_b = L_s i_b - M (i_a + i_c)$ (19)

$\lambda_c = L_s i_c - M (i_b + i_a)$ (20)

where Ls is the self-inductance/phase, M is the mutual inductance of the motor winding/phase. As PMBLDCM has no neutral connection, Hence,

$i_a + i_b + i_c = 0$ (21)

Equations. From (14-21) the voltage between neutral terminal (n) and junction-point of the DC link is given as,

$v_{no} = \{v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})\}/3$ (22)

From Eqs. (18-21), the flux linkages are given as,

$\lambda_a = (Ls+M)\ i_a$, $\lambda_b = (Ls+M)\ i_b$, $\lambda_c = (Ls+M)\ i_c$, (23)

From Eqs. (15-17 and 23), the current derivatives in generalized state space form are given as,

$p_{ix} = (v_{xn} - i_x R - e_x n)/(Ls+M)$ (24)

where x represents phases a, b or c.

The developed electromagnetic torque T_e in the PMBLDCM [1-5] is given as,

$Te = (e_{an}\ i_a + e_{bn}\ i_b + e_{cn}\ i_c)/\ \omega r$ (25)

where ωr is motor speed in rad/sec.

The back electromotive forces may be given as a function of rotor position (θ) as,

$e_{xn} = K_b\ f_x(\theta)\ \omega r$ (26)

where x can be any phase a, b or c and accordingly fx(θ) denotes function of rotor position with a maximum value ±1, which is similar to trapezoidal induced emf given as,

$fa(\theta) = 1$ for $0 < \theta < 2\_/3$ (27)

$fa(\theta) = \{(6/\pi)(\pi - \theta)\} - 1$ for $2\pi/3 < \theta < \pi$ (28)

$fa(\theta) = -1$ for $\pi < \theta < 5\pi/3$ (29)

fa(θ) = {(6/π)(θ-2π)}+1 for 5π/3 < θ < 2π (30)

The functions fb(θ) and fc(θ) are identical to fa(θ) with a phase difference of 120o and 240o respectively.

Therefore, the electromagnetic torque is given as below,

$Te = K_b\{fa(\theta)\, i_a + fb(\theta)\, i_b + fc(\theta)\, i_c\}$ (31)

The mechanical equation of motion in speed derivative form is given as,

$p_{\omega r} = (P/2)\,(T_e - T_L - B\omega r)/(J)$ (32)

and the derivative of the rotor position angle is given as,

$p_\theta = \omega_r$ (33)

where P is number of poles, TL is load torque in Nm, J is moment of inertia in kg-m2 and B is friction coefficient in Nms/Rad. These equations (15-33) represent the dynamic model of the PMBLDC motor.

V. PERFORMANCE EVALUATION OF PROPOSED TOPOLOGY

The modeling of PMBLDCM drive is simulated in Matlab- Simulink. For showing the performance of the non-isolated bridgeless converters, PMBLDCM drive is fed with a PMBLDCM of 2 hp, 5.2 Nm rated torque is taken into consideration. The simulation of the complete drive is carried out in Matlab-Simulink environment for speed control of the PMBLDCM operated with a constant torque load. The complete information of the PMBLDC motor are given in power: 2 hp, rated torque: 5.2 Nm, poles: 4, resistance: 1.78 ohm/ph., inductance (L+M): 0.01859 H/ph., back EMF constant (K_b): 1.23 Vsec/rad, moment of inertia (J) = 0.013 Kg-m2. Source impedance (Z_s): 0.03 pu, switching frequency of PFC switch (fs) = 40 kHz. The performance of the PFC converters based PMBLDCM drive is simulated for the rated torque (5.2 Nm) at multiple speeds and input AC voltages while keeping DC link voltage constant at 300 V.

VI. PERFORMANCE OF BRIDGELESS CONVERTER FED PMBLDC MOTOR

The performance analysis of the designed PMBLDCM drive fed from a 220 V AC mains at the time of starting at rated torque and 1000 rpm speed is shown in Fig. 5. It is analyzed that the motor achieves a reference speed smoothly while keeping the stator current and electromagnetic torque within the specified limits i.e. double the rated value. The current waveform at input AC mains (I_s) is in same phase with the supply voltage (V_s).

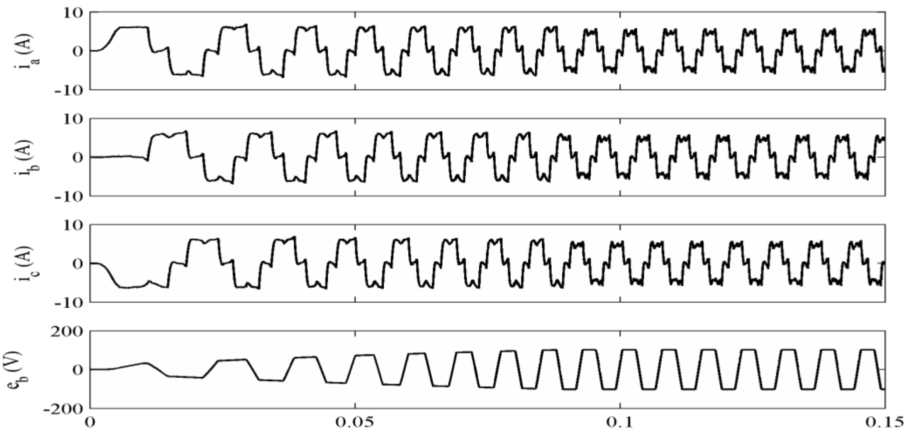

Fig. 5a

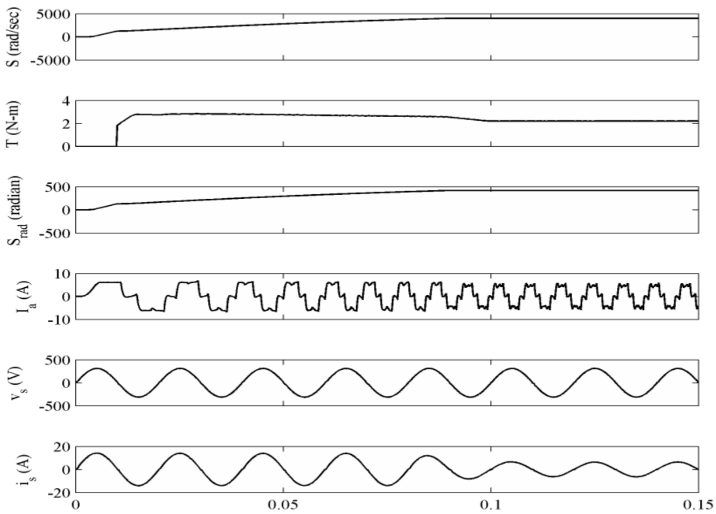

Fig.5b

Fig. 5 Steady-state performance of the proposed bridgeless boost converter-fed BLDC motor drive (Figs. 5a and b)

VII. CONCLUSION

A bridgeless converter has been designed for speed control of a PMBLDCM using the reference speed as an equivalent voltage at DC link. A high-efficiency bridgeless three-level PFC rectifier and a control system were introduced and theoretical analysis and experimental results were also represented. By using the novel configuration, the proposed rectifier performs the power conversion through one power-processing stage with high efficiency and low harmonic components. The speed of PMBLDCM has been found proportional to the DC link voltage, thereby a smooth speed control is observed while controlling the DC link voltage.

Appendix

PARAMETERS AND COMPONENTS OF PROTOTYPE

Parameters	Symbols	Value
Rated power	Po	1 kW
DC link voltage	V_{dc}	400 V
Input voltage	v_{in}	240 V
Frequency	fg	50 Hz
Switching frequency	f_s	25 kHz
DC-link capacitance	C_1 , C_2	810 μF
Filter inductance	L_f	0.89 mH

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