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RESEARCH ARTICLE

A UNIVERSAL BLDC MOTOR DRIVE WITH OPTIMIZED PERFORMANCE

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ABSTRACT

In this paper, an enhanced input converter circuit for Brushless DC motor drive system is presented. Drive's converter circuit is designed in such a way to realize all the standards of input power system. Based on the signals frominput voltage divider, converter generates a constant DC bus voltage to drive the Brushless DC motor. Drive's inverter designed with SPWM instead of square PWM, hence there is no pulsation torque. The experimental results are presented to verify the stability of the driver system. Various torque and RPM have been plotted during low voltage 110V and high voltage 230V.

INTRODUCTION

The permanent magnet (PM) motors have many advantages. Compared to DC motors, it requires lower maintenance due to the elimination of the mechanical commutation and it have a high-power density, making ideal for high torque-to-weight ratio applications. Compared to induction machines, which have lower inertia allowing faster dynamic response to reference commands. They are more efficient due to the permanent magnets, which result in virtually zero rotor losses [Brushless DC Motor Primer, 2008]. There are two kinds of PM motors, the permanent magnet synchronous motor (PMSM) and the brushless DC (BLDC) motor. Both have a permanent magnet on the rotor and require alternating stator currents to produce developed torque. The difference between the two is that the PMSM and the BLDC have sinusoidal and trapezoidal back-EMFs, respectively. The BLDC motor has the advantage of being a simple machine with higher power density, simple discrete position sensors, and simple control compared to a sinusoidal machine [PadmarajaYedamale, 2003]. However, its disadvantage is the pulsating torque problem [AVR1607: Brushless DC Motor (BLDC) Control in Sensor mode using ATxmega128A1 and ATAVRMC323, 2010]. In theory, these two machines can be driven by either sinusoidal or rectangle state current. Practically, the PMSM requires sinusoidal stator currents to produce constant torque. For a BLDC motor, due to finite phase induction, the sum of the commutating currents is never constant and this is the reason for the generation of pulsation torque. The increment of current in one phase as a result of the other two phase commutation can sometimes be fatal. An improved implementation of direct torque control (DTC) to a permanent-magnet, brushless DC (BLDC) drive is introduced in reference [PadmarajaYedamale, 2005]. The commutation torque ripple is minimized by combining the conventional two-phase switching mode with a controllable three-phase switching mode during periods when the phase currents are being commutated. A strategy for reducing commutation torque ripple in a position sensor-less BLDC motor drive is proposed in reference [FCM8201 Three-Phase Sine-Wave BLDC Motor Controller, 2011]. The BLDC motor has been more and more popular for the outdoor fan application field because of low cost and high efficiency. BLDC motors are very popular in a wide variety of applications. Compared with a DC motor, the BLDC motor uses an electronic commutation rather than a mechanical commutation, so it is more reliable than the DC motor. In a BLDC motor, rotor magnets generate the rotor's magnetic flux, so BLDC motors achieve higher efficiency. Therefore, BLDC motors may be used in high-end white goods (refrigerators, washing machines, dishwasher s, etc.), high-end pumps, fans, and in other appliances which require high reliability and efficiency.

EMF generated in the BLDC motors and produced torque has below relation

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$E = 2NlrB\omega$

$T = \left(\frac{1}{2} i^2 \frac{dL}{d\theta}\right) - \left(\frac{1}{2} B^2 \frac{dR}{d\theta}\right) + \left(\frac{4N}{\pi} Brl\pi i\right)$ -------- (1)

where *N* is the number of winding turns per phase, *l* is the length of the rotor, *r* is the internal radius of the rotor, *B* is the rotor magnet flux density, *w* is the motor's angular velocity, *I* is the phase current, *L* is the phase inductance, θ is the rotor position, and R is the phase resistance.

There is a wide range of input voltages to consider for worldwide operation and tolerances (usually 10%) must be included! The peak working voltage maximum at the input to the converter is V_{RMS} x √2. The range for a universal input power supply is 90 V_{RMS} to 264 V_{RMS}. Wide ranging operation without a line-select switch is possible at power levels less than 100 W. While it may be technically possible to operate above 100 W over the wide input-voltage range, circuit losses and limitations that increase cost usually dictate a 110 V/220 V switch (Fig. 1) to select a full-wave bridge or voltage-doubler configuration. When closed, the switch enables the circuit to double the 110 V/120 V input, thus making the DC working voltage approximately the same as it would be for 220 V/230 V input with the switch open.

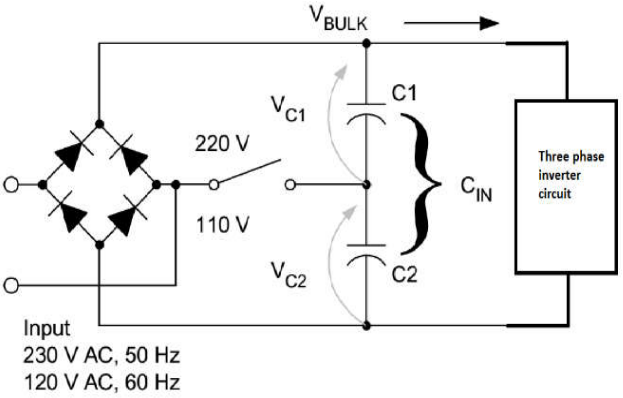

Figure 1. Basic circuit for universal input

Table 1. Global level of Working Voltage

Area	V_{RMS} (Typ)	±10%	Working Voltage (V_{DC})
Japan	100	90 to 110	126 to 154
US	120	108 to 132	151 to 184
Europe	220	198 to 242	277 to 390
India	230	207 to 253	289 to 358
China	220	198 to 242	277 to 390
Africa	240	216 to 264	306 to 373
Australia	230	207 to 253	289 to 358

Voltage Doubler design for converter input stage

Converter stage of BLDC drive will have voltage doubler based charge pump. This is designed in view of lowest available voltage from input utility supply to get standard output. Most optimum charge pump for this purpose is Two Phase Voltage Doubler (TPVD). The basic circuit of single stage charge pump shown in the Fig. 1-a. Here we use rectifier diodes for switching element and controlled as per input ac cycles. Number of capacitors used in a charge pump, is related to the energy needed to drive the pump of desired voltage level. Since the energy stored in a capacitor is proportional to the product of the capacitance value, and square of the voltage across the capacitance, we can estimate the total energy delivered to an N -stage Dickson charge pump (Janusz A. Starzyk *et al.*, 2001) including the energy stored in the load resistor using

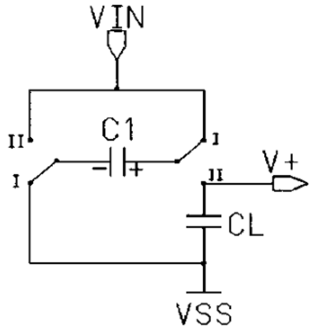

Figure 2-a

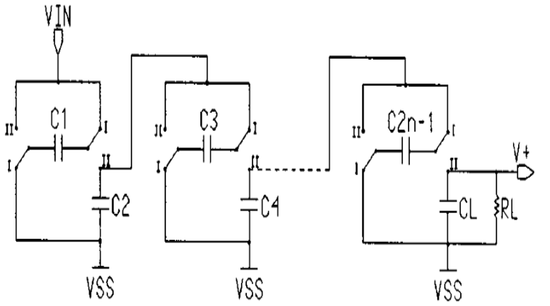

Figure 2-b

$$W_D = \sum_{i=1}^{N-1} \frac{1}{2} C[V(i)][V(i)]^2 + \frac{1}{2} C_{load}(NV_{in})^2$$

$= \sum_{i=1}^{N} \frac{1}{2} C(iV_{in})^2 = \frac{N(N+1)(N+2)}{12} CV_{in}^2$ --------------(2)

where in order to simplify discussion, we assumed that C= $C_{load.}$ By comparison, the total energy delivered to a single-stage TPVD charge pump with the same voltage gain can be estimated from

$W = \frac{1}{2} CV_{in}^2$ -----------------------------------(3)

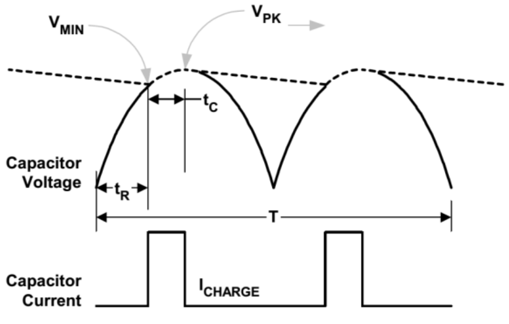

Figure 3. Charge pump capacitor waveforms

Power Transfer Optimization

The charge pump circuit analysis by figure 2-b and equation 2, 3 are obtained under the assumption that there is no power loss in the charge pump circuits, and that the electric charge transfer is instantaneous. After the output of such a charge, the pump reaches its maximum voltage level, there will be no energy driven from the supply source. In the real-world application, charge pumps will drive electronic devices that can be treated as resistive or sometimes R-C loads. A simple way to estimate the effect of the resistive load on the operation of a charge pump is to solve the output circuit equation considering the output resistance R_{load} and the equivalent charge pump circuit (shown in Fig. 9(a)). By estimating the equivalent capacitance C_{eq}, the electric charge dissipated by the load resistor R_{load} during a clock period can be evaluated from

$$Q_R = V_o C_{eq}\left(1 - exp\left(-\frac{T}{R_{load}C_{eq}}\right)\right) \qquad \text{----------------(4)}$$

Where Vo is the output voltage when R_{load} is absent, and T is the clock period. After evaluating Q_R, we can modify the Q–V realm equations as follows:

$CV = Q - Q_Rd$

$$C_{eq} = \frac{Q_d}{V_0}$$

For the inverter load above expression will be

$$C_{eq} = \frac{I_{peak}}{V_o}\tau \qquad \text{--------------------------------------(5)}$$

Since the optimum power is obtained at the same voltage level for a given charge pump, we can find dependence between the output power level and the optimum load resistance using

$$P_o = \frac{V_{out}^2}{R_{load}} = KfC \ \rightarrow\rightarrow \ R_{load} = \frac{V_{out}^2}{KfC} \qquad \text{------------ (6)}$$

where is a constant for a given charge pump organization and is independent on the number of stages (in the TPVD design K $\approx 15.4V^2$). This indicates that the optimum load resistor is in inverse proportion to the values of the charge pump capacitance used.

Prototype development

BLDC motor drive for power tool application where 115 Nm torque with free speed of 660 RPM to be delivered. There is shift-down speed of 10% to achieve target torque. So output power required will be 800 Watt with peak of 1.5kW. Dc bus is designed for 350 V so bleeder resistor is calculated from eq. 6 as 10 times of R_{load}. Charge pump equivalent capacitors are calculated from eq. 5 for peak load current of 35A at 10 milli second duration which is computed as 720 µF. This is equated at standard value of 1000 µF. DC bus formed using 1000 µF /500 V series -parallel combination of electrolytic capacitors in four numbers. For the initial trial an electro-mechanical relay is used instead of triac for switching voltage doubler ON when input voltage detected lower than 190V which is the maximum possible value of 120V power system standard.

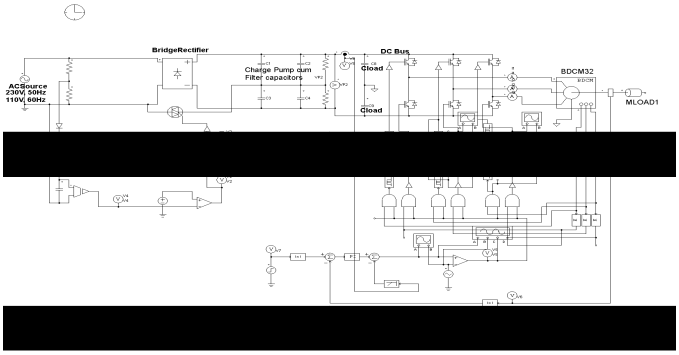
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Figure 4. Schematic of modified converter in the BLDC drive

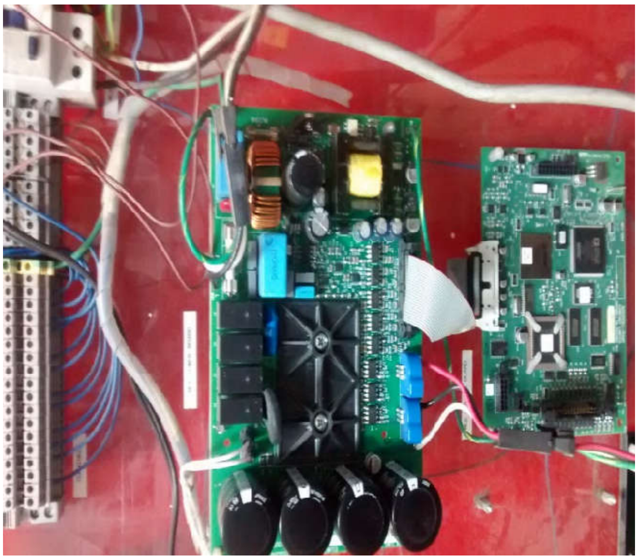

Figure 5. Prototype board of BLDC power drive with modified input converter circuit

System output and Analysis

Prototype system has been tested with 230V, 50 Hz input as well as 120V. 60 Hz and captured data for 30 tightening cycles of power tool. Motor specifications of the power tool are as in the Table-2. There were no torque ripples even when voltage doubler circuit was actuated. This could be achieved as voltage doubler charge pump was sufficient to maintain DC bus voltage between 300V to 350V.

Table 2. Motor specs in the experimental setup

DC bus voltage	Rated RPM of motor	Running RPM	Motor resistances
350	660rpm	428rpm	Ru=Rv=Rw= 1.5Ω±10%

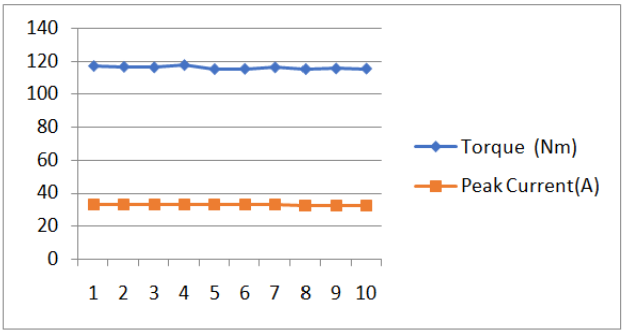

Figure 6. Output Torque and drive current at 110V input supply

Figure 6 shows the drive current and output torque during ten cycles. Target torque of 115 Nm was achieved at peak current of 32A which is actually at stalled motor torque.

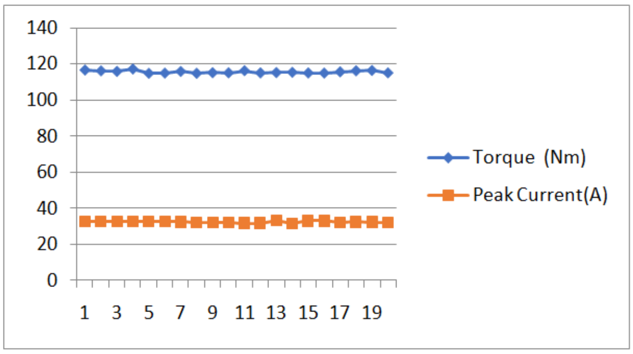

Figure 7. Output Torque and drive current at 230V input supply

Figure 7 shows the drive current and output torque during twenty cycles. Target torque of 115 Nm was achieved at peak current of 33A which is actually at stalled motor torque.

Conclusion

In this paper, a converter stage of BLDC motor power drive is analyzed. From the experimental results, it is evident that the controlled voltage doubler is an optimum cost effective solution for developing a universal drive. It is found that all the power system standards globally can be accommodated using this circuit. The current drawnand torque produced are almost same during the operation with and without voltage doubler charge pump. This drive has been tested in the power tools with torqueing load of 115 Nm at 660 RPM. In both the conditions torque ripple as well as current drawn was of the same order. This was achieved as DC bus voltage was constant. This development will enable BLDC motor drive to accept any power system voltage standards throughout the world without compromising its performance which we can evident from data presented in Figure 6 and 7.

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