A LOW COST BRUSHLESS PERMANENT MAGNET (BPM) MOTOR DRIVE SYSTEM USING TMS320F240

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***Abstract*-**In this paper the performance of a brushless permanent magnet (BPM) motor drive system based on TMS320F240 has been analyzed. A brushless permanent magnet motor provides a unique opportunity to designer to develop a low cost system with high system reliability. Such a system can find a lot of applications especially in consumer applications like washing machines. The converter used is a low cost thyristor based load commutated inverter (LCI). The utility side consists of a single-phase controlled rectifier, while a three-phase current source inverter is used to drive the motor. A detailed digital computer program using SABER to simulate the motor drive system was developed. In the program, the LCI and the BPM motor plus the control strategy were fully modeled. The developed control strategy has been successfully implemented using TMS320F240. Experimental results to support the application of LCI to drive a BPM motor is included in the paper. The performance of drive under both steady state and dynamic condition is analyzed with special emphasis on startup.

I. INTRODUCTION

The permanent magnet brushless (BPM) variable speed drives have gained a lot of popularity in consumer applications mainly due to their higher reliability and adequate cost to performance ratio at high volume of production. The BPM motors are made by inverting the stator and rotor of PM dc commutator motor. Stator winding in a BPM motor is wound in a manner so that the back EMF is trapezoidal in shape. The rectangular current flowing through the stator windings thus produces the constant torque. A low cost permanent magnet such as ferrite can be used in the BPM motor for low cost applications. The trapezoidal shape of back-emf and the rectangular shape of stator currents allow for use of less expensive Hall effect sensors for position measurement.

The main disadvantage of BPM motor is narrow field weakening region, but it is possible to extend the field-weakening region by adding external inductance. This additional inductance adds to volume, cost and losses.

II. LOAD COMMUTATED INVERTER (LCI) DRIVE

This paper discusses the implementation of a thyristor based load-commutated inverter to supply 3-phase BPM motors [1-2]. The control of BPM drive supplied by LCI is much simpler; drive is compact and has lower losses compared to conventional PWM controlled voltage source inverters (VSI). Since most of the consumer products operate with single-phase input supply, the proposed drive uses a single-phase thyristor based rectifier in input stage as illustrated in Figure 1. Use of single-phase rectifier helps in further cost reduction. Eliminating bulky DC link capacitor and self-controlled switches are the distinct advantages for low cost of LCI, in addition to inherent regenerating capability. Similar to any current source topology LCI drive also has in-built current protection. The current sensor requirements for a current-regulated BPM drive are typically reduced to a single sensor. As only two devices are conducting at any instant, the current flowing through any of the conducting phase has same magnitude as that of the dc link current. The amplitude of currents can be adjusted by phase control of the input rectifier.

The BPM motor operates equally well both as a motor and as a generator. In case of high-speed operation, the amplitude of back-emf voltage for any BPM increases linearly with rotor speed. The current control for BPM motor drive gradually degrades when speed increases and sum of two conducting back-emfs approaches the dc link voltage. This reduction in torque can be compensated to some extent by advancing the current in on-coming phase relative to the back-emf voltages. This additional time allows the current to build up before back-emf voltage increases and stops further increase in current. The detail operation of a LCI drive is discussed in [3].

A high performance drive should have acceptable torque ripple, less input harmonics, reduced acoustic and electrical noise, which in turns depends upon the processing capabilities of the processor. An implementation of BPM-LCI drive needs at least ten gate signals, one ADC to sense the DC-link current, three digital inputs for Hall effect sensors and one additional digital input for Zero Crossing detector which synchronizes the gating of controlled rectifier with mains. The processor should be capable of performing fast multiplication and addition to successfully implement outer speed PI controller and inner current controller loop. In addition, processor requires to calculate speed using position information from Hall effect sensors. It also requires to generate gating signals for inverter using position information and gating signals for input rectifier depending upon speed feedback and input mains.

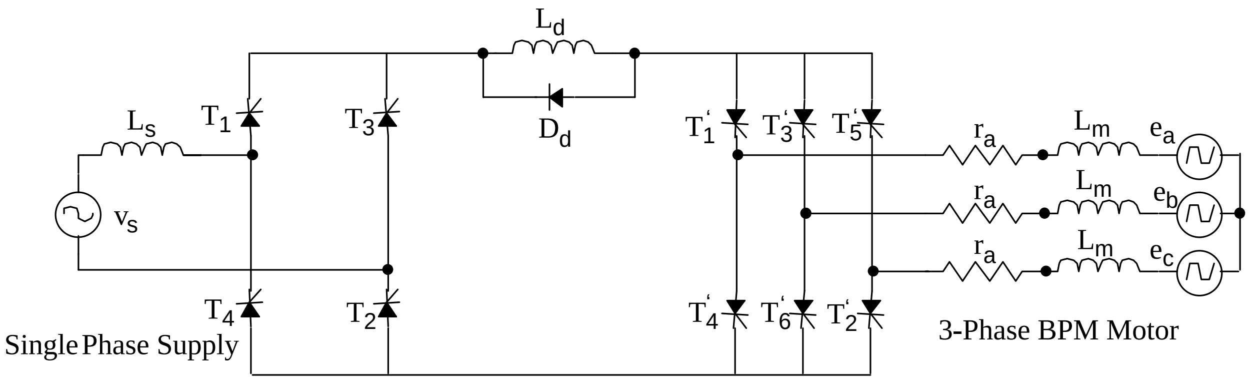

Figure 1: LCI-BPM motor drive with single-phase input.

A conventional micro-controller was first used, but lack of capture ports, low processing power lead to complexity in programming which left no room for implementation of sensorless algorithm. These days the trend is to use a Digital Signal Processor (DSP) designed for motor control applications, such as TMS320F240 [4]. Although, it is a fixed-point processor, it has on-chip ADC; four capture ports, three 16-bit hardware timers and 12 independent PWM outputs. These added features reduce a lot of programming, and therefore more processing time is available for implementation of PI controllers, sensorless speed detection techniques and torque profiling algorithms. On chip peripherals of TMS320F240, drastically reduces the over all chip count on the board to almost zero.

The system is built around TMS320C24x evaluation board. The evaluation module package includes a C-compiler, assembler and evaluation board with PC interface. In order to optimize the program all the modules are implemented in assembly language of TMS320F240.

III. CONTROL BLOCK DIAGRAM

Figure 2 illustrates the block diagram of the proposed BPM drive including Hall sensors as rotor position encoder. The drive employs an inner current loop with an outer speed loop. The current loop is 20 times faster than the speed loop. The output of Hall effect sensors and zero crossing detectors (ZCD) is given to the digital inputs of TMS320F240. These four digital inputs form a bus and any change in the digital value is used to change the firings sequence of thyristors (both inverter and rectifier). Since each Hall effect sensor changes its output at 60 mechanical degrees, time required for change in Hall effect outputs is proportional to speed of the motor. A 16-bit timer, Timer-2 of TMS320C240 is used in single up counting mode to calculate the motor speed ω_{fb} using the position information. An increase in speed command ω_{ref} produces a speed error $\Delta\omega$. A positive speed error leads to an increase in $I_{dc\_ref.}$. A positive I_{err} leads to a decrease in delay angle α of the phase-controlled rectifier. As the amplitude of motor phase current increases the machine accelerates till the actual speed reaches to the commanded speed. After that, the dc link current drops down to a value proportional to load torque. The outputs of speed and current PI controller regulated to limit the dc link current

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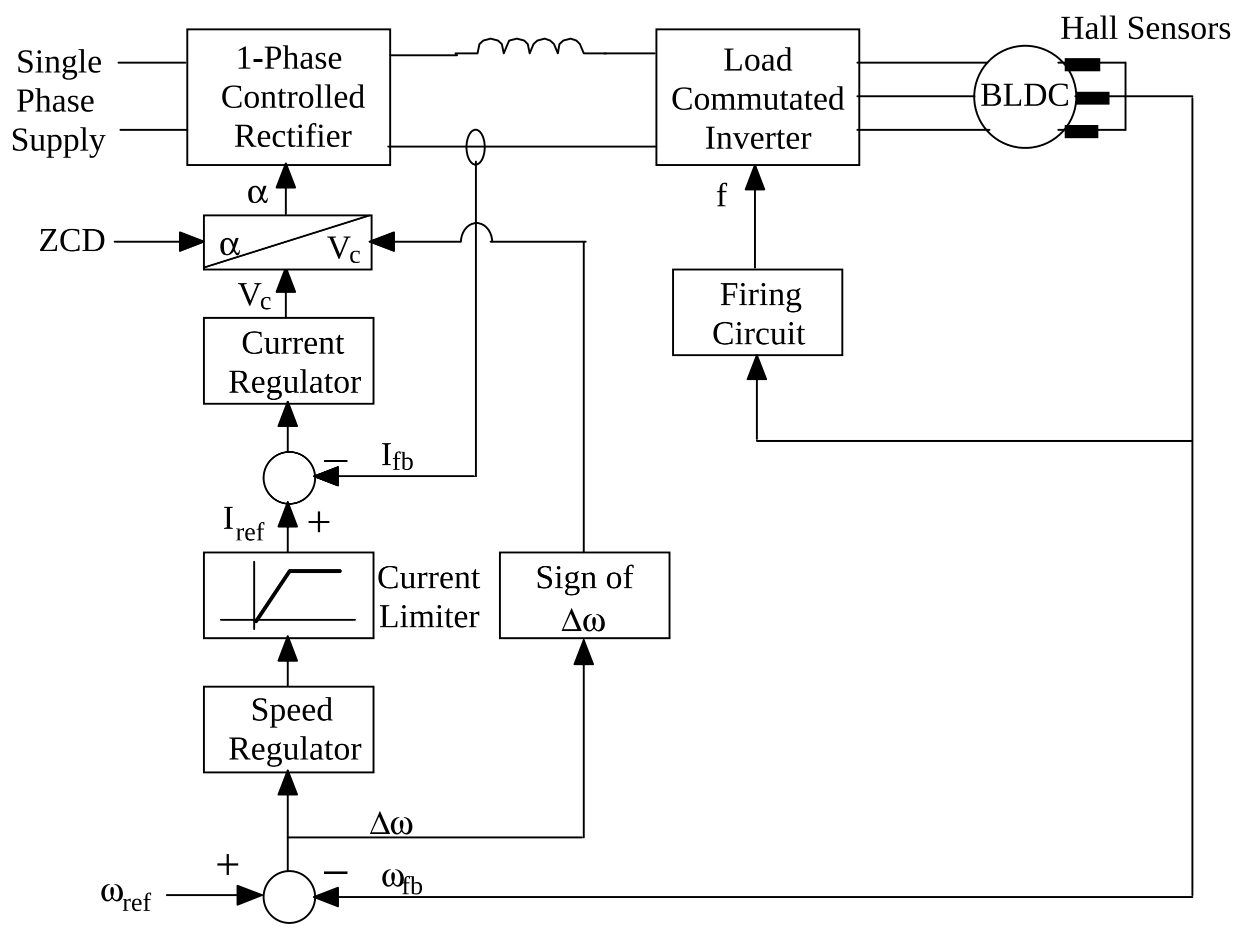

Figure 2 : Block diagram of the control system.

In this system base speed is reached when the output of the rectifier saturates. Typically the outputs of Hall effect sensor will be in phase with corresponding back-emfs. The speed above base speed is obtained by increasing the lead angle of the load-commutated inverter. It is practically impossible to trigger the device before controller gets a signal from Hall effect sensors. Therefore, in order to advance the phase current with respect to back-emf, the sensor position on motor shaft is adjusted in order to get an advancement of about 30^o electrical with respect to back –emf. Now it is easy to adjust the angle of advancement by introducing the delay when it is not needed.

At start-up and at low speeds (less than 10% of the full speed), specially for large motors, the induced EMF in the BPM motor is not sufficient to provide current commutation in the load converter [5,10]. Under this condition, the current commutation is provided by the line converter by going into an inverter mode and forcing the link current to become zero, thus providing turn-off of thyristors in the load side inverter. However, for fractional horse power motors the shaft inertia is not significant and as a result with the initial rotor kick, the back EMF will be large enough to result in a successful commutation of thyristors. Therefore, the dc link anti-parallel thyristor can be replaced with a diode simplifying the circuit further

IV. SIMULATION RESULTS

In order to study the performance of the proposed BPM-LCI drive, a detailed digital computer program using simulation package SABER [12] was developed. The parameters of the three-phase four-pole BPM motor are given in Appendix.

The computer simulation has been performed with a back-emf crest equal to 150 degrees. The dc link inductor value plays an important role in the overall performance of the drive. A larger dc link inductor will result in a more ripple free dc link current [13]. The line-end power factor of the input rectifier will be higher if the dc link current is continuous [13]. However, a large dc link inductor means increased volume and cost. Therefore, a compromise between inductor size and motor output torque ripple is needed. The dc link inductor used in the simulation was set to 200 mH.

Figure 3 shows the dc link current at no load condition. It becomes continuous at higher values of load torque or with higher dc link inductor.

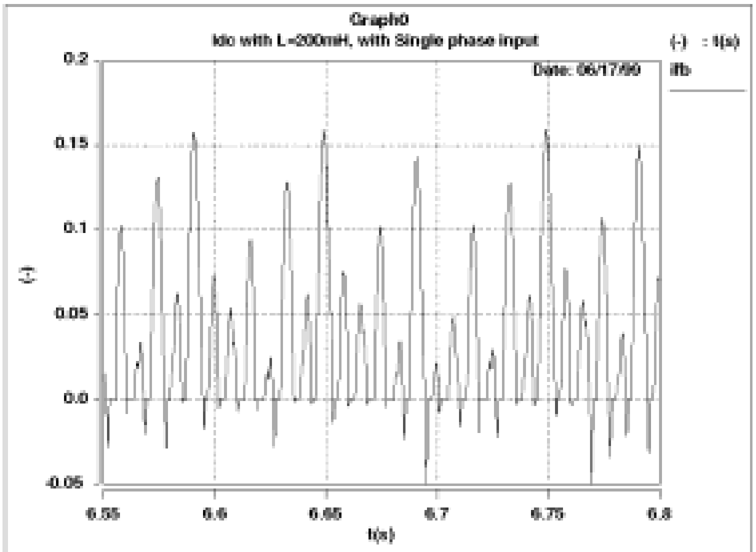

Figure 3: DC link current at no load.

As illustrated in speed response of Figure 4, the motor shaft speed closely follows the reference speed. At start up the motor shaft reaches the reference speed in about 250 msec under 50% of rated load. For a given load condition this time is a function of the saturation limit set on the output of Speed and Current PI controllers. These limits in practice are decided by the ratings of the thyristors used and limit on in-rush current of supply.

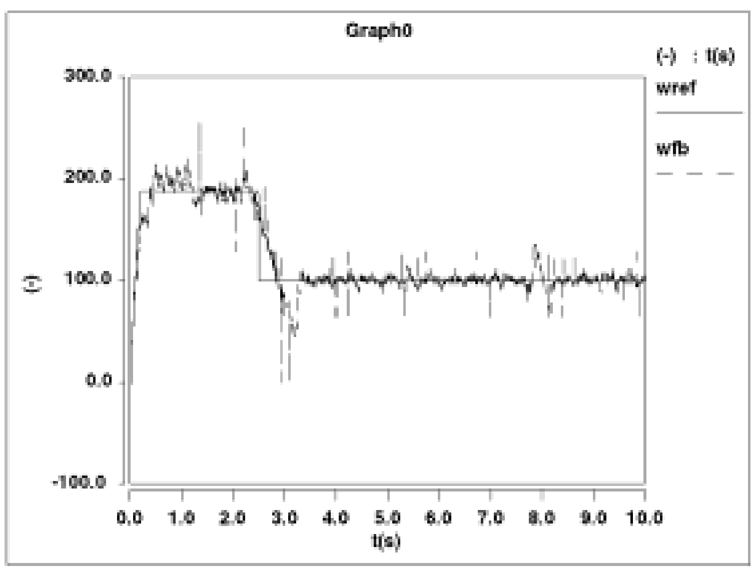

Figure 4: Speed response at no load.

Figure 5 shows the dynamic response for a sudden change in commanded speed. It also shows that a sudden load change of about 50% of the rated load hardly produces any change in the rotor speed.

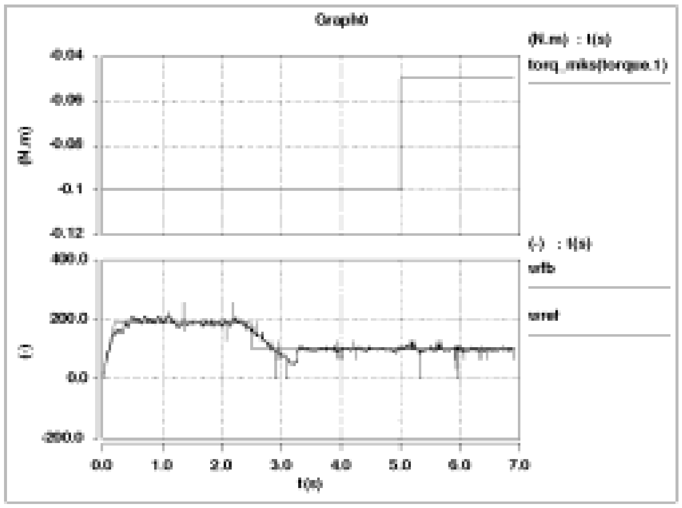

Figure 5: Dynamic speed response.

V. EXPERIMENTAL RESULTS

A load commutated inverter BPM motor drive was fabricated in the laboratory. The link inductance used was 140 mH. The control algorithm was implemented on a TMS320F240 evaluation board. A 5 kHz pulse train was used to turn on the thyristors that are isolated from the control circuits using pulse transformers. Figure 6 shows the dc link current and dc link voltage. The shaft speed was set to about 300 rpm under no load condition. The commutation spikes can be observed in the dc link voltage.

Figure 7 shows the dc link current at start up. As it can be seen after initial peak required for accelerating the motor to the commanded speed the current is almost constant. This value is proportional to load torque.

As illustrated in Figure 8 the input supply current at no load condition does not have any high frequency harmonics, thus eliminates need for input EMI filter.

Figure 9 and 10 shows the motor phase current and motor phase voltage at no load condition. As it can be observed the motor phase current is pulsating and goes to zero. At higher loads its shape resembles the ideal 120-degree step waveform.

Figure 11 illustrates the measured speed response at approximately 50% of the rated load.

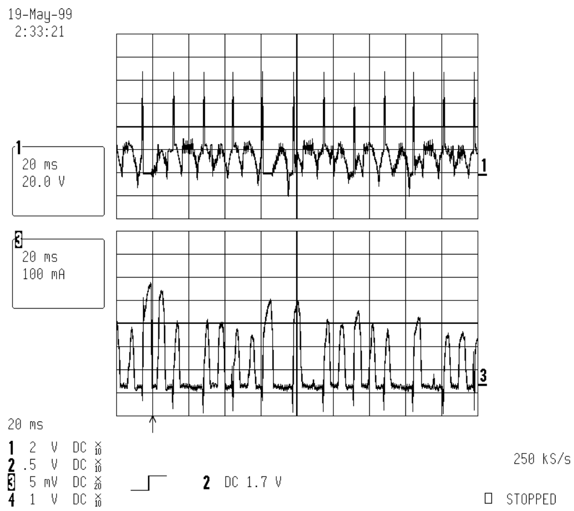

Figure 6: DC link voltage and DC link current at no load condition.

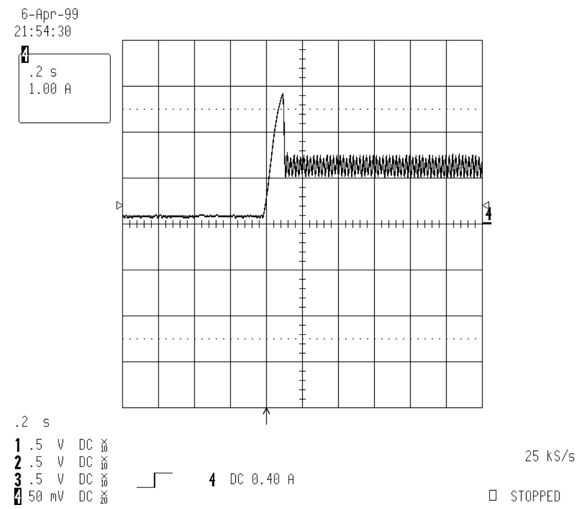

Figure 7: DC link current at start up.

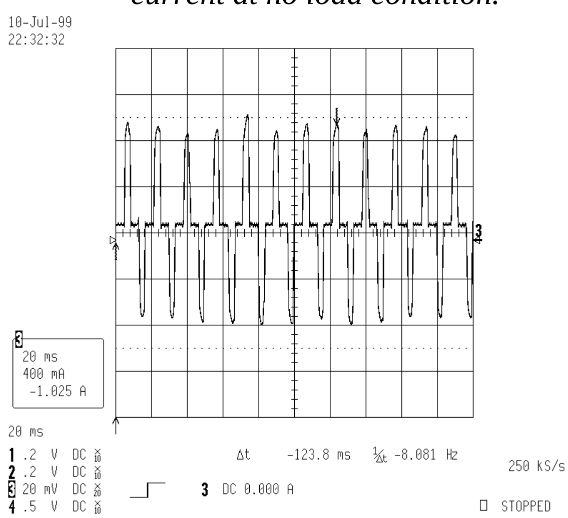

Figure 8: Input supply current at no load.

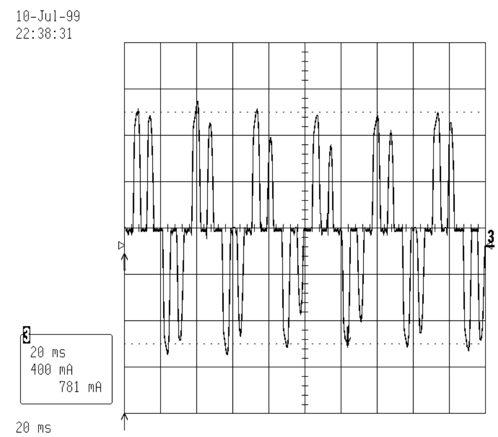

Figure 9: Motor phase current at no load.

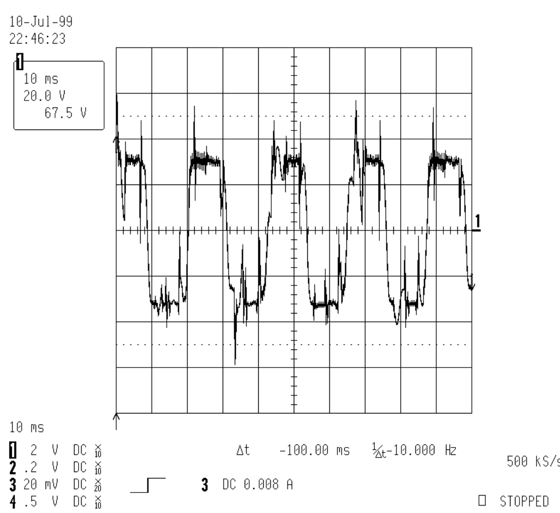

Figure 10: Motor phase voltage at no load.

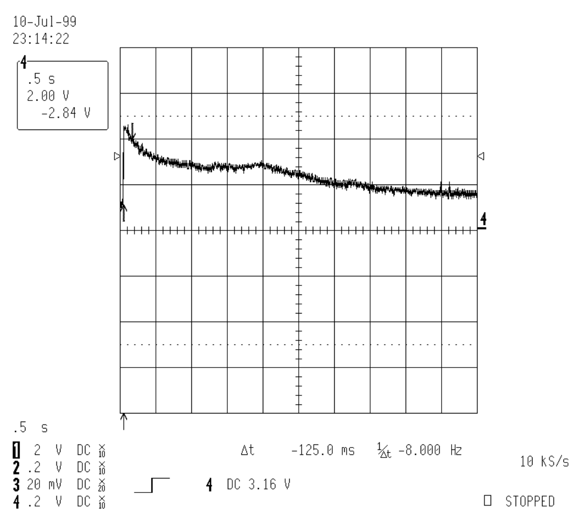

Figure 11: Motor speed at start up.

VI. CONCLUSIONS

In this paper, the performance of load commutated brushless permanent magnet motor drive with single phase input has been analyzed. A detailed digital computer program using SABER to simulate the motor drive system was developed. In the program, the LCI BPM motor plus the control strategy were implemented. The complete programming is done in assembly language. It was shown that there is no need for an anti-parallel dc link thyristor to operate the motor during start-up. Since the motor inertia is small the LCI-BPM motor drive can operate successfully even at starting. It was observed that a drive system designed around a specially designed DSP such as TMS320F240 requires almost no external hardware. This leads to a compact and less expensive system. Through extensive simulation and experimental results it was shown that the motor starts from stall under full load without any commutation failures.

VII. ACKNOWLEDGMENT

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Appendix

BPM motor parameters:

4 poles, 120 V, 1.5 A, 150 degree crest for back EMF

$r_a = 1.36\ \Omega$, $L_m = 12.5$ mH, $K_e = 0.259$ V.sec, $K_t = 0.259$ N.m/A, J = 0.000427 kg.m^2

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