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Efficient Control of PMBLDC Drive With Power Factor Correction Using Cuk Converter

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Abstract: ***Brushless DC electric motor also known as electronically commutated motors (ECMs, EC motors) are synchronous motors that are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor. The Cuk converter is a type of DC/DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. A cuk dc -dc converter topology reduced the power quality problems and improve the power factor at input ac mains. A three-phase voltage-source inverter is used as an electronic commutator operates the PMBLDCM drive The concept of voltage control at the dc link proportional to the desired speed of the PMBLDCM is used to control the speed of the compressor. The proposed power factor converter topology is designed, modeled and its performance is evaluated in matlab-simulink environment. The results show an improved power quality and good power factor in wide speed range of the drive. It also compares the Total Harmonic Distortion (THD) of the Input AC current with PID controller in Matlab-Simulink environment.***

Keywords: ***PFC, Cuk Converter, PMBLDC, voltage-source inverter, boost converter, Brushless motor and THD.***

Introduction:

A typical brushless motor has permanent magnets which rotate around a fixed armature, eliminating problems associated with connecting current to the moving armature. An electronic controller replaces the brush/commutator assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The controller performs similar timed power distribution by using a solid-state circuit rather than the brush/commutator system.

Brushless motors offer several advantages over brushed DC motors, including high torque to weight ratio, more torque per watt (increased efficiency), increased reliability, reduced noise, longer lifetime (no brush and commutator erosion), elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI). With no windings on the rotor, they are not subjected to centrifugal forces, and because the windings are supported by the housing, they can be cooled by conduction, requiring no airflow inside the motor for cooling. This in turn means that the motor's internals can be entirely enclosed and protected from dirt or other foreign matter.

Brushless motor commutation can be implemented in software using a microcontroller or microprocessor computer, or may alternatively be implemented in analogue hardware, or in digital firmware using an FPGA. Commutation with electronics instead of brushes allows for greater flexibility and capabilities not available with brushed DC motors, including speed limiting, "micro stepped" operation for slow and/or fine motion control, and a holding torque when stationary.

Because the controller must direct the rotor rotation, the controller requires some means of determining the rotor's orientation/position (relative to the stator coils.) Some designs use Hall effect sensors or a rotary encoder to directly measure the rotor's position. Others measure the back EMF in the undriven coils to infer the rotor position, eliminating the need for separate Hall effect sensors, and therefore are often called sensorless controllers.

In a Brushless DC motor, two coils are energized at a time with equal and opposite polarities, one pushes the rotor away from it while the other attracting the rotor towards it. This increases the overall torque capacity of the motor and Hall effect sensors or a rotary encoder determines which two coils have to be energized to achieve this strategy. A typical controller contains 3 bi-directional outputs (i.e. frequency controlled three phase output), which are controlled by a logic circuit. Simple controllers employ comparators to determine when the output phase should be advanced, while more advanced controllers employ a microcontroller to manage acceleration, control speed and fine-tune efficiency.

Controllers that sense rotor position based on back-EMF have extra challenges in initiating motion because no back-EMF is produced when the rotor is stationary. This is usually accomplished by beginning rotation from an arbitrary phase, and then skipping to the correct phase if it is found to be wrong. This can cause the motor to run briefly backwards, adding even more complexity to the startup sequence. Other sensorless controllers are capable of measuring winding saturation caused by the position of the magnets to infer the rotor position. Brushless motors fulfill many functions originally performed by brushed DC motors, but cost and control complexity prevents brushless motors from replacing brushed motors completely in the lowest-cost areas. Nevertheless, brushless motors have come to dominate many applications particularly devices such as computer hard drives and CD/DVD players. Small cooling fans in electronic equipment are powered exclusively by brushless motors. They can be found in cordless power tools where the increased efficiency of the motor leads to longer periods of use before the battery needs to be charged. Low speed, low power brushless motors are used in direct-drive turntables for gramophone records.

PMBLDCM is used to drive the air conditioner compressor, speed of which is controlled effectively by controlling the DC link voltage. Permanent Magnet Brushless Direct Current (PMBLDC) motors are one of the motor types rapidly gaining popularity. Permanent Magnet Brushless Direct Current (PMBLDC) is Air conditioning systems are typically the largest consumers of electrical energy in homes and office buildings. The most common type of air conditioning that we see is technically referred to as direct expansion, mechanical, vapor-compression refrigeration system.

BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. The compressor load is considered as a constant torque load equal to rated torque with the speed control required by air conditioning system. A 1.5 kW rating A few of these are Better speed versus torque characteristics, High dynamic response, High efficiency Long operating life, Noiseless operation, Higher speed ranges. This paper aims at an improve speed quality employing Cuk DC-DC converter is used as a power factor correction (PFC) converter for feeding a voltage source inverter (VSI) based permanent magnet brushless DC motor (PMBLDCM) driven air condition. This PFC converter is front end diode bridge rectifier (DBR) fed from single-phase AC mains and connected to a three phase voltage source (VSI) feeding the permanent magnet brushless DC motor (PMBLDCM). The PMBLDC Motor is used to drive a compressor load of an air conditioner through a three-phase VSI fed from a controlled DC link voltage. The speed of the compressor is controlled to achieve energy conservation using a concept of the voltage control at DC link proportional to the desired speed of the PMBLDC Motor.

The use of a permanent-magnet (PM) brushless dc motor (PMBLDCM) in low-power appliances is increasing because of its features of high efficiency, wide speed range, and low maintenance. It is a rugged three-phase synchronous motor due to the use of PMs on the rotor. The commutation in a PMBLDCM is accomplished by solid state switches of a three-phase voltage-source inverter (VSI). Its application to the compressor of an air-conditioning (Air-Con) system results in an improved efficiency of the system if operated under speed control while maintaining the temperature in the air conditioned zone at the set reference consistently.

Conversional DC motors are highly efficient and their characteristics make them suitable for use as servomotors. However, their only drawback is that they need a commutator and brushes which are subject to wear and require maintenance. When the functions of commutator and brushes were implemented by solid state switches, maintenance free motors were realized. These motors are now known as brushless DC motors. The construction of modern brushless motors is very similar to the AC motor, known as the permanent magnet synchronous motor.

The stator winding s are similar to those in a poly-phase ac motor, and the rotor is composed of one or more permanent magnets. Brushless DC motors are different from ac synchronous motors in that the former incorporates some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches as shown in fig.1.1. The most common position/pole sensor is the Hall element, but some motors use optical sensors.

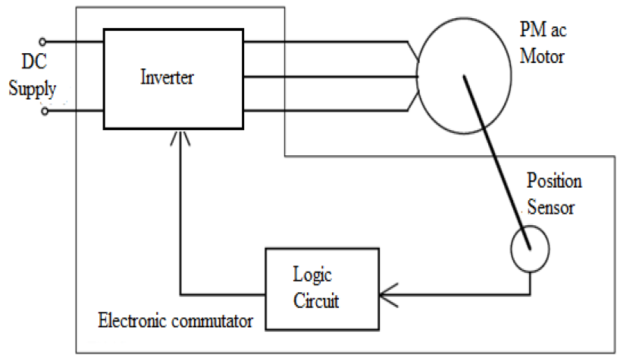

Figure : Permanent magnet brushless DC motor

The brushless dc motor is essentially configured as a permanent magnet rotating part a set of current carrying conductors. In this respect, it is equivalent to an inverted DC commutator motor, in that the magnet rotates while the conductors remain stationary. In both cases, the current must reverse polarity every time a magnet pole passes by , in order that the torque is unidirectional. In the DC commutator motor, the commutator and brushless perform the polarity reversal.

Brushless DC motors usually consist of three main parts:

- Stator
- Rotor
- Hall sensors

Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery. Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles.

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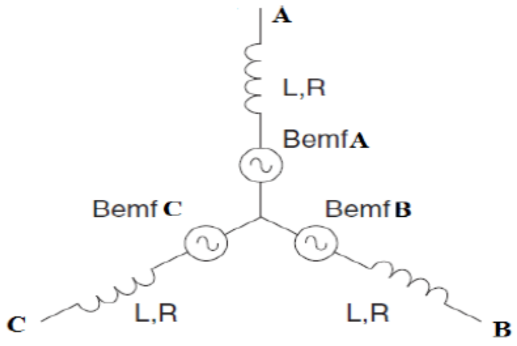

Fig : stator electrical configuration (three phases, three coils)

Rotor

The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate north (N) and south (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets.

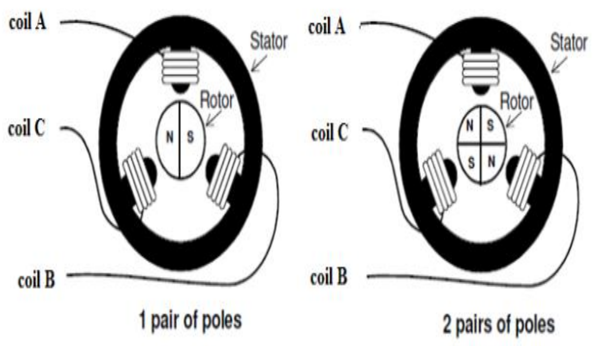

Fig : three phase three coil BLDC motor stator and rotor.

Hall Sensor

Unlike a brushed dc motor the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall Effect sensors embedded into the stator.

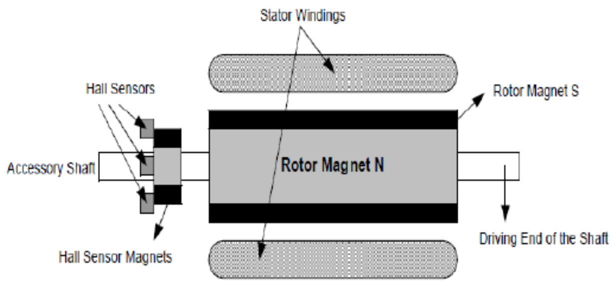

Figure : transverse section of BLDC

AIR-CONDITIONER

Air conditioning is the process of altering the propertie of air (primarily temperature and humidity) to more favorable conditions. More generally, air conditioning can refer to any form of technological cooling, heating, ventilation, or disinfection that modifies the condition of air. An air conditioner (often referred to as air con, AC or A/C, and not to be confused with the abbreviation for alternating current) is a majoror home appliance, system, or mechanism designed to change the air temperature and humidity within an area (used for cooling and sometimes heating depending on the air properties at a given time).

ELECTROMECHANICAL COOLING

Designed to improve manufacturing process control in a printing plant, Carrier's invention controlled not only temperature but also humidity. Carrier used his knowledge of the heating of objects with steam and reversed the process. Instead of sending air through hot coils, he sent it through cold coils (ones filled with cold water). The air blowing over the cold coils cooled the air, and one could thereby control the amount of moisture the colder air could hold. In turn, the humidity in the room could be controlled. The low heat and humidity helped maintain consistent paper dimensions and ink alignment.

CUK CONVERTER

The circuit setup is like a combination of the buck and boost converters. Like the buck-boost circuit it delivers an inverted output. Virtually all of the output current passes through C1, and as ripple current. So C1 is usually a large electrolytic with a high ripple current

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rating and low ESR (equivalent series resistance), to minimize losses. The main difference between the cuk and the other converters is that the cuk used a capacitor as the energy storing element.

Operating Principle

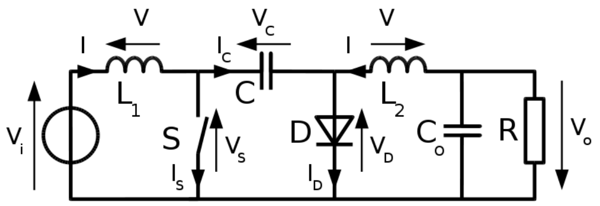

Fig. a non-isolated Cuk converter

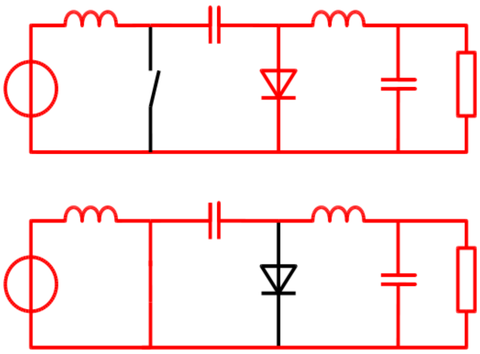

Fig. on & off state

When S is turned on, current flows from the input source through L1 and S, storing energy in L1's magnetic field. Then when S is turned off, the voltage across L1 reverses to maintain current flow. As in the boost converter current then flows from the input source, through L1 and D1, charging up C1 to a voltage somewhat higher than V_{in} and transferring to it some of the energy that was stored in L1. When S is turned on again, C1 discharges through via L2 into the load, with L2 and C2 acting as a smoothing filter. Meanwhile energy is being stored again in L1, ready for the next cycle. As with other converters (buck converter, boost converter, buck-boost converter) the Cuk converter can operate in two modes 1) continuous 2) discontinuous current mode. However, unlike these converters, it can also operate in discontinuous voltage mode (i.e., the voltage across the capacitor drops to zero during the commutation cycle).

PROPOSED CONCEPT

The commutation in a PMBLDCM is accomplished by solid state switches of a three-phase voltage-source inverter (VSI). Its application to the compressor of an air-conditioning (Air-Con) system results in an improved efficiency of the system if operated under speed control while maintaining the temperature in the air conditioned zone at the set reference consistently. The Air-Con exerts constant torque (i.e., rated torque) on the PMBLDCM while operated in speed control mode. The Air-Con system with PMBLDCM has low running cost, long life, and reduced mechanical and electrical stresses compared to a single-phase.

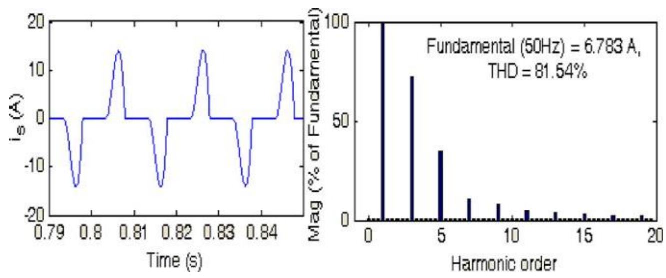

Fig.: Current waveform at ac mains and its harmonic spectra for the PMBLDCM drive (PMBLDCMD) without PFC.

Induction motor-based Air-Con system operating in "on/off" control mode. A pmbldcm has the developed torque proportional to its phase current and its back electromotive force (EMF), which is proportional to the speed. Therefore, a constant current in its stator windings with variable voltage across its terminals maintains constant torque in a PMBLDCM under variable speed operation. A speed control scheme is proposed which uses a reference voltage at dc link proportional to the desired speed of the permanent-magnet brushless direct current (PMBLDC) motor. However, the control of VSI is only used for electronic commutation based on the rotor position signals of the PMBLDC motor. The PMBLDCMD is fed from a single-phase ac supply through a diode bridge rectifier (DBR) followed by a capacitor at dc link. It draws a pulsed current as shown in Fig. above, with a peak higher than the amplitude of the fundamental input current at ac mains due to an uncontrolled charging of

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the dc link capacitor. This results in poor power quality (PQ) at ac mains in terms of poor power factor (PF) of the order of 0.728, high total harmonic distortion (THD) of ac mains current at the value of 81.54%, and high crest factor (CF) of the order of 2.28. Therefore, a PF correction (PFC) converter among various available converter topologies, is almost inevitable for a PMBLDCMD. Moreover, the PQ standards for low power equipments, such as IEC 61000-3-2, emphasize on low harmonic contents and near unity PF current to be drawn from ac mains by these drives. There are very few publications regarding PFC in PMBLDCMDs despite many PFC topologies for switched mode power supply and battery charging applications. This paper deals with an application of a PFC converter for the speed control of a PMBLDCMD. For the proposed voltage controlled drive, a Cuk dc–dc converter is used as a PFC converter because of its continuous input and output currents, small output filter, and wide output voltage range as compared to other single switch converters. Moreover, apart from PQ improvement at ac mains, it controls the voltage at dc link for the desired speed of the Air-Con.

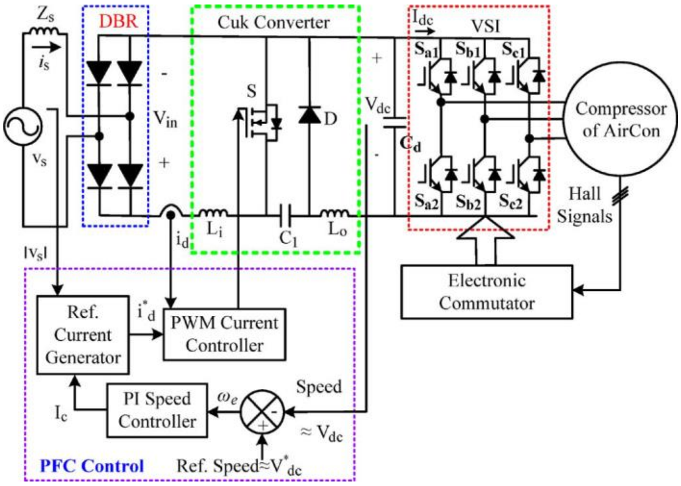

Fig. Control scheme of the proposed Cuk PFC converter-fed VSI-based PMBLDCMD.

The detailed modeling, design, and performance evaluation of the proposed drive are presented for an air-conditioner driven by a 0.816-kW 1500-r/min PMBLDC motor.

PROPOSED SPEED CONTROL SCHEME OF PMBLDC MOTOR FOR AIR-CONDITIONER

Fig. above shows the proposed speed control scheme which is based on the control of the dc link voltage reference as an equivalent to the reference speed. However, the rotor position signals acquired by Hall-effect sensors are used by an electronic commutator to generate switching sequence for the VSI feeding the PMBLDC motor, and therefore, rotor position is required only at the commutation points. The Cuk dc–dc converter controls the dc link voltage using capacitive energy transfer which results in nonpulsating input and output currents. The proposed PFC converter is operated at a high switching frequency for fast and effective control with additional advantage of a small size filter. For high-frequency operation, a metal–oxide–semiconductor field-effect transistor (MOSFET) is used in the proposed PFC converter, whereas insulated gate bipolar transistors (IGBTs) are used in the VSI bridge feeding the PMBLDCM because of its operation at lower frequency compared to the PFC converter. The PFC control scheme uses a current multiplier approach with a current control loop inside the speed control loop for continuous-conduction-mode operation of the converter. The control loop begins with the processing of voltage error (Ve), obtained after the comparison of sensed dc link voltage (Vdc) and a voltage (V dc) equivalent to the reference speed, through a proportional–integral (PI) controller to give the modulating control signal (Ic). This signal (Ic) is multiplied with a unit template of input ac voltage to get the reference dc current (Id) and compared with the dc current (Id) sensed after the DBR. The resultant current error (Ie) is amplified and compared with a Saw tooth carrier wave of fixed frequency (fs) to generate the pulse width modulation (PWM) pulse for the Cuk converter. Its duty ratio (D) at a switching frequency (fs) controls the dc link voltage at the desired value. For the control of current to PMBLDCM through VSI during the step change of the reference voltage due to the change in the reference speed, a rate limiter is introduced, which limits the stator current of the PMBLDCM within the specified

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value which is considered as double the rated current in this work.

Results

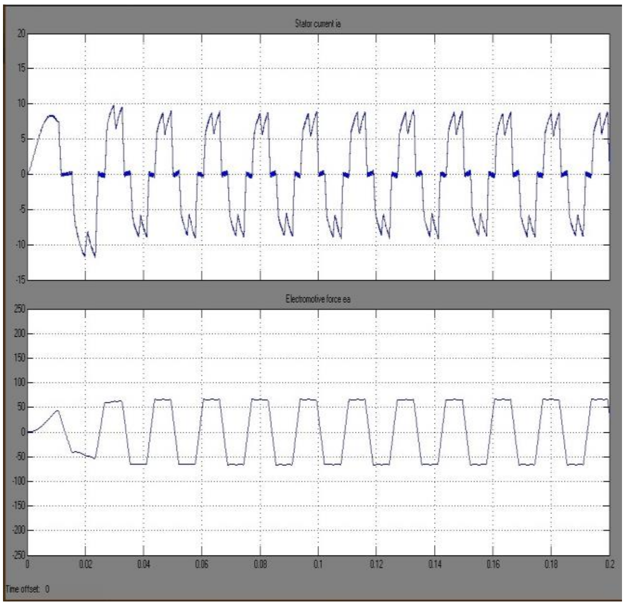

Figure: waveform of (a) Stator Current Ia, (b) Electromotive Force Ea.

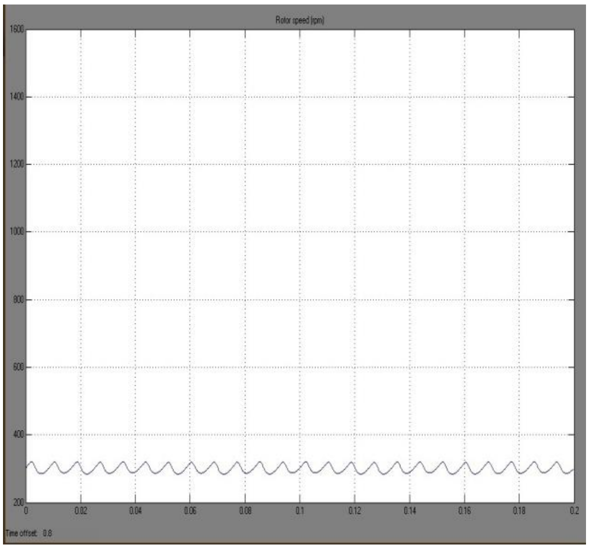

Figure : waveform of rotor speed (rpm)

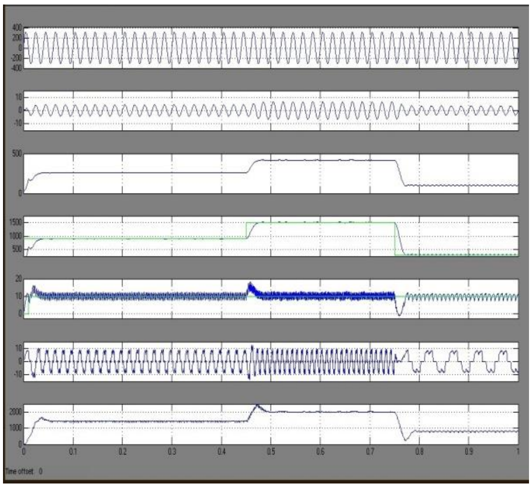

Figure: simulation output for efficient control of pmbldc drive with power factor correction using cuk converter.

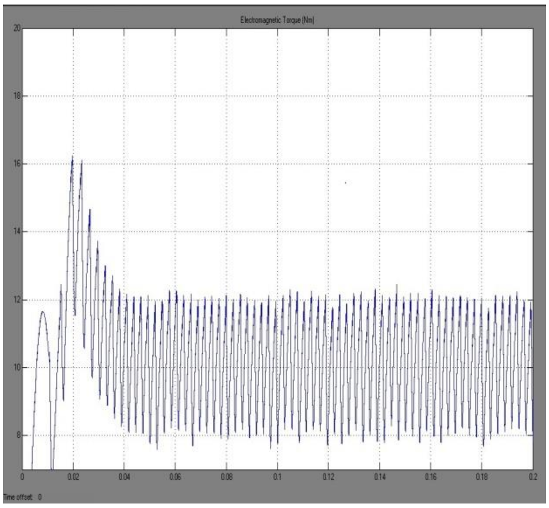

Figure : waveform of Electromagnetic Torque N-m

CONCLUSION

A new speed control strategy for a PMBLDCMD using the reference speed as an equivalent voltage at dc link has been simulated for an air-conditioner employing a Cuk PFC converter and experimentally validated on a developed controller. The speed of PMBLDCM has been found to be proportional to the dc link voltage; thereby, a smooth speed control is observed while controlling the dc link voltage. The introduction of a rate limiter in the reference dc link voltage effectively limits the motor current within the desired value during the transient conditions. The PFC Cuk converter has ensured near unity PF in a wide range of the speed and the input ac voltage. Moreover, PQ indices of the proposed PFC drive are in conformity to the International Standard IEC 61000-3-2. The proposed PMBLDCMD has been found as a promising variable speed drive for the Air-Con system. Moreover, it may also be used in the fans with PMBLDC motor drives on the trains recently introduced in Indian Railways. These PMBLDC motor drive based fans have similar PQ problems as they use a simple single-phase diode rectifier and no speed control. These fans also have inrush current problems. All these PQ problems of poor PF, inrush current, and speed control in these fans on the trains in Indian Railways may be mitigated by the proposed voltage-controlled PFC Cuk converter-based PMBLDCMD.

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