A Fuzzy Based PFC CUK Converter for Voltage Controlled Adjustable Speed PMBLDCM Drive

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Abstract: This paper deals with the method used to improve the speed quality and the efficiency of BLDC motor drive by implementing fuzzy based controller with power factor correction technique. A CUK dc-dc converter is used as a single-stage power-factor-correction converter for a permanent magnet brushless dc motor (PMBLDCM) fed through diode bridge rectifier from a single-phase ac mains. This reduced the power quality problems and improves the power factor at input ac mains. A three-phase voltage-source inverter is used as an electronic commutator which switches 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 stator current of the PMBLDCM during step change of the reference speed is controlled within the specified limits by an addition of a rate limiter in the reference DC link voltage. The proposed power factor converter topology is designed, modelled and its performance is evaluated in Matlab-Simulink environment for an air conditioner driven through a PMBLDC motor. The results show an improved power quality and good power factor in wide speed range of the drive.

Key Words: Air-conditioner (Air-Cons), CUK converter, power factor (PF) correction (PFC), permanent-magnet (PM) brushless dc motor (PMBLDCM), voltage-source inverter (VSI), Fuzzy controller.

I. INTRODUCTION

Air-conditioners (Air-Cons) constitute a considerable amount of load in AC distribution system. However, most of the existing air-conditioners are not energy efficient and thereby, provide a scope for energy conservation. Air-Cons in domestic sector are usually driven by a single-phase induction motor; the temperature in the air conditioned zone is regulated over a hysteresis band through the ‘on/off’ control of the compressor motor. Therefore, the motor is operated only at full load (compressor ‘on’) at nearly constant speed, i.e., rated speed, [1] because these motors achieve maximum efficiency near the rated load only. The ‘on/off’ control provides inefficient temperature control with increased losses in the motor during frequent ‘on/off’ operation. Efforts to improve the efficiency of the existing air-con system using new mechanical and electronic system designs have resulted in marginal improvement in system efficiency; however, the variable speed operation of the air conditioner significantly improves system efficiency [2]. Moreover, the compressor driven by a motor with speed control delivers the desired cooling capacity and maintains the room temperature effectively and efficiently. Permanent magnet brushless DC motor (PMBLDCM) drives are being employed in many variable speed applications due to their high efficiency, silent operation, compact size, high reliability, ease of control, and low maintenance requirements. It is a good option for an air conditioner compressor.

Figure 1: Current waveform at AC mains and its harmonic spectra for the PMBLDCMD without PFC.

PMBLDCM is operated through a three-phase voltage source inverter (VSI), which is fed from single phase AC supply using a diode bridge rectifier (DBR), followed by a smoothing DC link capacitor (Fig.1). PMBLDCM is supplied by three-phase rectangular current blocks of 120° duration, in phase with the constant part of the back EMF waveform. These motors need rotor-position information only at the commutation points, e.g., every 60° electrically in the three-phase, requiring a simple controller for commutation [3-7]. The PMBLDC motor is operated at a constant torque (i.e., rated torque) with speed control to improve energy efficiency [8]. In fact, the back-EMF of the PMBLDCM is proportional to the motor speed and the developed torque is proportional to its phase current [3-6]; therefore, a constant torque is maintained by a constant current in the stator winding of the PMBLDCM, whereas the speed can be controlled by varying the terminal voltage of the motor. A new speed control scheme that uses DC link voltage proportional to the desired speed of the PMBLDC motor is used in this work. VSI control is based on the rotor position signals and used only for electronic commutation of the PMBLDC motor.

The most commonly used topology for PMBLDCM Drive fed from single-phase AC mains uses a diode bridge rectifier (DBR) followed by a smoothing DC capacitor. It draws a pulsed current as shown in Figure 1, with a peak higher than the amplitude of the fundamental input current at ac mains due to an uncontrolled charging of 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 with 67% efficiency of the drive. Therefore, many Power Quality (PQ) problems arise at input AC mains including poor power factor, increased Total Harmonic Distortion (THD) and high Crest Factor (CF) of AC mains current etc. These PQ problems as addressed in IEC 61000-3-2 especially in low power appliances become severe for the utility when many such drives are employed simultaneously at nearby locations[9]. Therefore, PMBLDCM drives having inherent Power Factor Correction (PFC) become the preferred choice for the Air-Con. The PFC converter draws sinusoidal current from AC mains in phase with its voltage.

In this PFC converter a DC-DC converter topology is mostly used amongst several available topologies with variations of capacitive/inductive energy transfer (e.g. boost, buck-boost, Cuk, SEPIC, zeta converters). It results in an improved performance, such as reduction of AC mains current harmonics, acoustic noise, electromagnetic interference (EMI) and improved efficiency, wide input voltage range utilization etc. This paper deals with an application of a PFC converter for the speed control of a PMBLDCM. 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 [10]–[12]. Moreover, apart from PQ improvement at ac mains, it controls the voltage at dc link for the desired speed of the Air-Con with the help of suitable fuzzy logic controller. So an attempt is made to remove the drawbacks associated with sensed control[14] and use of traditional controllers by using sensorless control and fuzzy controller for PMBLDC motor. Thus this method of sensorless control of PMBLDC will provide advantages like cost reduction, reliability, elimination of difficulty in maintaining the sensor etc. and developing nonlinear system for embedded control.

In recent years, the number and variety of applications of Fuzzy Logic (FL) have increased significantly. To understand why use of Fuzzy Logic has grown, it must be first understood as what is meant by Fuzzy Logic. Fuzzy Logic has two different meanings. In a narrow sense, Fuzzy Logic is a logical system, which is an extension of multivalve logic. However, in a wider sense Fuzzy Logic is almost synonymous with the theory of Fuzzy sets, a theory which relates to classes of objects with un sharp boundaries in which membership is a matter of degree. In this perspective, Fuzzy logic in its narrow sense is a branch of Fuzzy Logic. Even in its more narrow definition, Fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

II. PROPOSED SPEED CONTROL SCHEME OF PMBLDC MOTOR FOR AIR-CONDITIONER

The proposed control scheme is shown in Fig. 2 with the commutation control in VSI and speed control (i.e., voltage control) with PFC through a DC-DC converter. The CUK converter controls the DC link voltage as well as performs PFC action by its duty ratio (D) at a constant switching frequency (fs). The proposed PFC control scheme employs a current control loop inside the voltage control loop in the continuous conduction mode(CCM) operation of the PFC converter.

A Fuzzy Logic (Fuzzy) controller forms an integral part of this controller which processes the voltage error resulting from the comparison of set voltage reference and sensed voltage at DC link. The resultant control signal of Fuzzy controller is multiplied with a unit template of input AC voltage and compared with DC current sensed after the DBR. The resultant current errors amplified and compared with a saw-tooth carrier wave of fixed frequency (fs) for generating the PWM pulses for controlling switch of PFC converter. Use of a high switching frequency results in a fast control of DC link voltage and effective PFC action along with additional advantage of reduced size magnetics and filters. The optimum switching frequency is decided by various factors such as the switching device, switching losses and operating power level. A metal oxide field effect transistor (MOSFET) is used as the switching device for the proposed PFC converter. The proposed speed control scheme (as shown in Fig. 1) controls reference voltage at DC link as an equivalent reference speed, thereby replaces the conventional control of the motor speed and a stator current involving various sensors for voltage and current signals. Moreover, to generate the switching sequence for the VSI here introduce zero crossing back emf detection method and thus eliminating conventional position sensor requirement.
The DC link voltage is controlled by a half-bridge buck DC-DC converter based on the duty ratio (D) of the converter. For a fast and effective control with reduced size of magnetic and filters, a high switching frequency is used; however, the switching frequency (\(f_s\)) is limited by the switching device used, operating power level and switching losses of the device. Metal oxide field effect transistors (MOSFETs) are used as the switching device for high switching frequency in the proposed PFC converter. However, insulated gate bipolar transistors (IGBTs) are used in VSI bridge feeding PMBLDCM, to reduce the switching stress, as it operates at lower frequency compared to PFC switches. The PFC control scheme uses a current control loop inside the speed control loop with current multiplier approach which operates in continuous conduction mode (CCM) with average current control. The control loop begins with the comparison of sensed DC link voltage with a voltage equivalent to the reference speed. The resultant voltage error is passed through a Fuzzy Logic (Fuzzy) controller to give the modulating current signal. This signal is multiplied with a unit template of input AC voltage and compared with DC current sensed after the DBR. The resultant current error is amplified and compared with saw-tooth carrier wave of fixed frequency (\(f_c\)) in unipolar scheme to generate the PWM pulses for the CUK converter. For the current control of the PMBLDCM during step change of the reference voltage due to the change in the reference speed, a voltage gradient less than 800 V/s is introduced for the change of DC link voltage, which ensures the stator current of the PMBLDCM within the specified limits (i.e. double the rated current).

### III. DESIGN OF PFC CUK CONVERTER BASED PMBLDCM

The proposed PFC Cuk converter is designed for a PMBLDCM with main considerations on the speed control of the Air-Con and PQ improvement at ac mains. The dc link voltage of the PFC converter is given as

\[ V_{dc} = V_{in}D/(1 - D) \]  

(1)

where \(V_{in}\) is the average output of the DBR for a given ac input voltage (Vs) related as

\[ V_{dc} = 2V/\pi \]  

(2)

The Cuk converter uses a boost inductor (\(L_i\)) and a capacitor (\(C_1\)) for energy transfer. Their values are given as

\[ L_i = DV_{in}/[f_c \Delta I_{Li}] \]  

(3)

\[ C_1 = D/L_i/[f_s \Delta I_{C1}] \]  

(4)

Where \(\Delta I_L\) is a specified inductor current ripple, \(\Delta V_{C1}\) is a specified voltage ripple in the intermediate capacitor (C1), and \(I_{C1}\) is the current drawn by the PMBLDCM from the dc link. A ripple filter is designed for ripple-free voltage at the dc link of the Cuk converter. The inductance (\(L_c\)) of the ripple filter restricts the inductor peak-to-peak ripple current (\(\Delta I_{Lc}\)) within a specified value for the given switching frequency (\(f_s\)), whereas the capacitance (\(C_d\)) is calculated for the allowed ripple in the dc link voltage (\(\Delta V_{cd}\)) [9, 13]. The values of the ripple filter inductor and capacitor are given as

\[ L_0 = (1 - D) / [f_s \Delta I_{Lo}] \]  

(5)

\[ C_d = I_{dc} / [2 \Delta V_{cd}] \]  

(6)

The PFC converter is designed for a base dc link voltage of

\[ V_{dc} = 298 \text{ V at } V_{in} = 220 \text{ V for } f_c = 40 \text{ kHz, } I_s = 4.5 \text{ A, } \Delta I_{L1} = 0.45 \text{ A (10\% of } I_s), \Delta I_{Lo} = 3.5 \text{ A (}= I_{Lo}), \Delta V_{Cd} = 4 \text{ V (1\% of } V_{in}), \text{ and } \Delta V_{C1} = 220 \text{ V (}= V_{in}). \]  

<table>
<thead>
<tr>
<th>Design Values</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_{Lo})</td>
<td>0.82 mA</td>
</tr>
<tr>
<td>(C_d)</td>
<td>1590 μF</td>
</tr>
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</table>

### IV. TECHNIQUES IN SENSORLESS CONTROL

The BLDC motor provides an attractive candidate for sensorless operation because the nature of its excitation inherently offers a low-cost way to extract rotor position information from motor terminal voltages. A Permanent Magnet brushless drive that does not require position sensors but only electrical measurements is called a sensorless drive [15]. For three-phase BLDC motor at one time instant, only two out of three phases are conducting current and the no conducting phase carries the back-EMF. If the zero crossing of the phase back EMF can be measured, we can know when to commutate the current. Sensing methods for the PM BLDC motors and generators are classified in two categories; direct and indirect back-EMF detection [15]. Direct back-EMF detection methods: the back-EMF of floating phase is sensed and its zero crossing is detected by comparing it with neutral point voltage. The methods can be classified as:

- Direct back-EMF detection methods are
  - Back-EMF Zero Crossing Detection (ZCD) or Terminal Voltage Sensing and PWM strategies.[16]

### V. DESIGN OF FUZZY CONTROLLER

Error (E) and change in error (CE) are the inputs for the fuzzy controller whereas the output of the controller is
change in duty cycle (ΔDC). The error is defined as the
difference between the ref speed and actual speed, the
cchange in error is defined as the difference between the
present error and previous error and the output, Change
in duty cycle ΔDC is which could be either positive or
negative is added with the existing duty-cycle to
determine the new duty-cycle (DC_new).

3. Rule Base And Inferenceengine: A rule base (a set of If-
Then rules), which contains a fuzzy logic quantification
of the expert’s linguistic description of how to achieve
control action. Once the rules have been established, a
fuzzy logic system can be viewed as a mapping from
inputs to outputs. Rules may be provided by experts or
can be extracted from numerical data. The performance
of the controller can be improved by adjusting the
membership function and rules.

Different types of inferential procedures to help us
understand things or to make decisions, there are many
different fuzzy logic inferential procedures. The fuzzy
inference operation is implemented by using the 49
rules.

Some of these rules are
1. If error (E) is NB and change in error(CE) is NB
then output is PB.
2. If error (E) is NB and change in error(CE) is NM
then output is PB
3. If error (E) is NB and change in error(CE) is NS
then output is PB
4. If error (E) is NB and change in error(CE) is NS
then output is PM

Likewise 49 rules are defined. The same set of rules
could be presented in a sliding mode format, a more
compact representation given in Table 1.

Table 1. Rule Base

<table>
<thead>
<tr>
<th>Error(E)</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>Z</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
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</thead>
<tbody>
<tr>
<td>NB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
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<td>NB</td>
<td>NB</td>
<td>NB</td>
</tr>
</tbody>
</table>

Defuzzification: Finally the fuzzy output is converted
into real value output by the process called
defuzzification. Centroid method of defuzzification is
used because it can be easily implemented and requires
less computation time. The defuzzified output is
obtained by the following equation

\[ Z = \frac{\sum_{i=1}^{n} \mu(x) \cdot x}{\sum_{i=1}^{n} \mu(x)} \]
Where z is the defuzzified value, μ(x) is the membership value of member x [5].

VI. MATLAB/SIMULINK MODELLING AND SIMULATION RESULTS.

Fig: 5 MATLAB/SIMULATION model of the PFC CUK converter based PMBLDC

Fig: 6. Figure shows the waveform for the voltage across source

Fig: 7. Shows the waveform for the current across the source

Fig: 8. Shows the waveform for the electromagnetic torque.

Fig: 9. Shows the waveform for the stator current

Fig: 10. Shows the fuzzy controlled waveforms (source voltage, source current, dc voltage, speed, torque, back EMF, power) for different speeds (500, 1000 rpm)

VII. 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 simulation validation on a fuzzy based intelligence 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 of the fuzzy controller in the reference dc link voltage effectively limits the motor current with in the desired value during the transient conditions (starting and speed control); we get better response as well as better THD values. The PFC Cuk converter has ensured near unity PF in a wide range of the speed and the input ac voltage. These PMBLDC motor drive based fans have similar PQ problems as they use a simple single-phase diode rectifier and no speed control. Moreover, using the intelligence controllers we get better response and error should be nullified as well as THD values also.

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VIII. REFERENCE


