1. INTRODUCTION

Several types of electric motors have been proposed for high performance drive applications. The Slip Energy Recovery System (SERS) known as Scherbius system is low cost, simple control circuitry and high efficiency even at low speeds [1]. The Slip Energy Recovery System consists of a wound rotor induction machine, a diode-bridge rectifier, a large link inductance, a thyristor-bridge inverter and an optional 3-phase transformer. A SERS routes power that is normally wasted in the rotor of an induction machine back to the AC supply to improve overall drive efficiency. In addition, using a step-down transformer between the AC supply and the inverter module, the voltage ratings of the inverter and rectifier devices may be made significantly smaller than the rated machine stator voltages. Thus, in contrast to a stator-voltage-controlled induction machine drive, the relative power electronic units of the SERS may be designed to be smaller, lighter and less expensive [2]. The problem of SERS is that it has lower power factor, in general 0.4 to 0.6 more or less. In literature [3], “Adaptive Fuzzy Techniques for Slip-Recovery Drive Control” has been proposed by using a six-thyristor bridge, supplemented by GTO across the dc terminal. This system regulates the slip energy recovery and the power factor of the system, for all regimes. A fuzzy adaptive control, based in a three levels control structure improves the drive performance as the system evolves. However, the six-pulse converter used in [3] has a problem that the high harmonics will occur in the system. It is known that the harmonics will increase the losses in the form of copper losses and core losses, and the harmonic losses added will result in more heat in the motor. Consequently, the less harmonics of the current will cause the less heat in the motor so that the efficiency and the life span can be kept.

This paper proposes a Modified Slip Energy Recovery System (MSERS) in order to improve its power factor, to reduce harmonics of line current waveforms, to smoothen direct current in DC link circuit and to improve the drive performance of MSERS by using fuzzy technique based chopper control as follows: The power factor can be improved by using the chopper type IGBT applied across the DC terminal and then the chopped DC is fed to the converter operating as an inverter. The harmonics are reduced by using twelve-pulse line commutated converter which composes of 2 sets of six-pulse line commutated converter. One set is supplied through the wye-wye connected transformer and the other set is supplied through the wye-delta connected transformer. The purpose of wye-delta transformer connection is to introduce a 30 phase shift between the source and the bridge. The drive performance of MSERS is improved by employing 2 sets of fuzzy logic controllers. From Fig.3, one set of fuzzy logic controller is used in the inner loop for controlling the torque of the motor which is proportional to DC link current, and another set is used in the outer loop for controlling the actual motor speed. Therefore, the fuzzy logic controllers in the paper will result the higher accuracy in controlling the chopper.

2. MODIFIED SLIP ENERGY RECOVERY SYSTEM (MSERS)

For reduction in output harmonics can be accomplished by using two six-pulse bridge as shown in fig. 1. This configuration is called a twelve-pulse converter. One of the bridge is supplied through a Y-Y connected transformer, the other supplied through a Y-Δ transformer as shown. The purpose of Y-Δ transformer connection is to introduce a 30 phase shift between the source and the bridge. The results in an input to the two bridges which are 30 apart. The two bridge outputs are similar, but also shifted by 30. The overall output voltage is the sum of the two bridge outputs. The delay angles for the bridges are typically the same.

The DC output is the sum of the dc output of each bridge.

\[ V_i = \frac{V_{dc1} + V_{dc2}}{2} = \frac{3\sqrt{2}V_{L-L}\cos \alpha + 3\sqrt{2}V_{L-L}\cos \alpha}{\pi a_f} \]

\[ = \frac{3\sqrt{2}V_{L-L}}{\pi a_f} \cos \alpha \]
The peak output of the twelve-pulse converter occurs midway between alternate peaks of the six-pulse converters. Adding the voltages at that point for \( D = 0 \) gives

\[
V_{i,\text{peak}} = V_{m,\text{L-L}} \cos \left( 15^\circ \right) = 0.966 V_{m,\text{L-L}} .
\]

The current in the ac lines supplying the Y-Y transformer is represented by the Fourier series

\[
i_y(t) = \frac{2\sqrt{3}}{\pi} i_o \left( \cos \omega_o t - \frac{1}{5} \cos 5\omega_o t + \frac{1}{7} \cos 7\omega_o t \right.
\]

\[
\left. - \frac{1}{11} \cos 11\omega_o t + \frac{1}{13} \cos 13\omega_o t - \ldots \right) \quad (4)
\]

The current in the ac lines supplying the Y-\( \Delta \) transformer is represented by the Fourier series

\[
i_\Delta(t) = \frac{2\sqrt{3}}{\pi} i_o \left( \cos \omega_o t + \frac{1}{5} \cos 5\omega_o t - \frac{1}{7} \cos 7\omega_o t \right.
\]

\[
\left. - \frac{1}{11} \cos 11\omega_o t + \frac{1}{13} \cos 13\omega_o t - \ldots \right) \quad (5)
\]

Thus, some of the harmonics on the ac side are canceled by using the twelve-pulse scheme rather than the six-pulse scheme. The harmonics that remain in the ac system are of order \( 12k \pm 1 \). Cancellation of harmonics \( 6(2n-1) \pm 1 \) has resulted from this transformer and converter configuration. From fig. 1, the rotor current can be given as

\[
i_2 = \sqrt{\frac{2}{3}} I_{dc,\text{dott}} = \sqrt{\frac{2}{3}} I_{dc} \quad (7)
\]

The expression for rotor circuit copper loss is

\[
P_{R12} = 3\left( \sin \frac{2}{3} \right) \left( 2SR_1 + R_2 \right) \quad (8)
\]

where \( I_2 = \sqrt{\frac{2}{3}} I_{dc} \) relation has been used to replace in equation (7).

\[
P_{R12} = 3\left( \sin \frac{2}{3} \right) \left( 2SR_1 + R_2 \right) = 2\left( SR_1 + R_2 \right) I_{dc}^2 \quad (9)
\]

where \( 2(SR_1 + R_2) \) is equivalent resistance of motor winding transfer to DC link circuit. The voltage drop at DC link circuit is given as

\[
V_{\text{drop}} = \frac{3S(X_1 + X_2)}{\pi} I_{dc} \quad (10)
\]

Therefore, the expression for power is given

\[
P_{\text{drop}} = V_{\text{drop}} I_{dc} = \frac{3S(X_1 + X_2)}{\pi} \frac{2}{\sin \frac{2}{3}} I_{dc} \quad (11)
\]

In the view of Fig. 1, a device called chopper type IGBT is applied to SERS in order to improve power factor. The symmetric chopper method that controls the IGBT to turn on and off is adopted to adjust the duty cycle of chopper under a certain fixed inverting firing angle \( \alpha \).

3. ANALYSIS OF THE CIRCUIT

The mathematical model of system are analysis with consider from equivalent circuit diagram of dc link.
Fig. 2 The proposed MSERS.

From the circuit in Fig.2, the rectifier voltage $V_d$ and DC voltage of inverter $V_i$ can be written respectively as

$$V_{dc} + V_{chop} = 0$$

$$\frac{1.35}{a_m} V_s + \frac{1.35}{a_T} (1 - D)V_s \cos \alpha = 0$$

where $V_s$ is the stator voltage, $a_T$ is the turn ratio of the transformer, $D$ is the duty cycle of the chopper and $\alpha$ is firing angle of the converter. Since the slip of the motor is

$$S = -\frac{a_m}{a_T}(1-D)\cos \alpha$$

where $a_T$ is the turn ratio of the motor. The speed of the motor can be controlled by changing the inverted voltage $V_i$ at the intermediate DC link or by changing the duty cycle.

The power recovery $P_{inv}$ and the power factor $\cos \varphi$ will be derived respectively. The total resistance $R_m$ in DC link circuit can be expressed

$$R_m = \left(\frac{2R_1 + 3\pi (X_1 + X_2)}{s} + 2R_2 + R_f\right)$$

Then the DC current $I_{dc}$ in DC link is

$$I_{dc} = \frac{V_{dc} - V_{chop}}{R_m} = \frac{1.35}{a_m} \frac{SV_s}{a_T} - \frac{1.35}{a_T} (1 - D)V_s \cos \alpha$$

and the power factor

$$\cos \varphi = \frac{P_1 - P_{inv}}{\sqrt{(P_1 - P_{inv})^2 + (Q_1 + Q_{inv})^2}}$$

It can be respectively obtained, where $P_1$ is the active power, $Q_1$ is the reactive power and where

$$Q_{inv} = \sqrt{\frac{18}{\pi}} V_s (1 - D) I_{dc} \sin \alpha$$

It is seen from equation (17) that the $Q_{inv}$ is decreased according to the duty cycle $D$ while the fixed firing angle $\alpha$ has been fixed. This cause the power factor shown in equation (16) is increased. Hence, the proposed MSERS can be utilized to improve the power factor effectively.

4. DESIGN OF A FUZZY LOGIC CONTROLLER

The drive performance of MSERS is improved by employing 2 sets of fuzzy logic controllers. From Fig.3, one set of fuzzy logic controller is used in the inner loop for controlling the torque of the motor which is proportional to DC link current $I_{dc}$, and another set is used in the outer loop for controlling the actual motor speed $w_m$. Therefore, the fuzzy logic controllers in the paper will result the higher accuracy in controlling the chopper. A fuzzy logic controller is proposed to control the speed of the motor to be constant when the load varies. The speed error $e(k)$ and the change of speed error $ce(k)$ are processed through the fuzzy logic controller whose output is the voltage command $V_d^*$. The current error is usually processed by current regulator to produce a control voltage $V_c$. This control current adjusts the duty cycle of chopper such that the desired speed of the motor can be obtained.
The universe of discourse of all the variables, covering the whole region, is expressed in per unit values. All the MFs are asymmetrical because near the origin (steady state), the signals require more precision. There are seven MFs for e(pu) and ce(pu) signal, whereas there are nine MFs for the output. All the MFs are symmetrical for positive and negative values of the variables. Figure 5 shows the corresponding rule table for the speed controller. The top row and left column of the matrix indicate the fuzzy sets of the variables e and ce, respectively, and the MFs of the output variable du(pu) are shown in the body of the matrix. There may be $7^2 = 49$ possible rules in the matrix, where a typical rule reads as

IF e(pu) is PS AND ce(pu) is NM THEN du(pu) is NS

Some blocks in the rule table may remain vacant, giving less number of rules.

5. EXPERIMENTAL RESULTS

The proposed control scheme is implemented to a three phase wound rotor induction motor which has the detail as follows: 0.22 kW, 230/440V, 1.12/0.6 A, $V_2= 100V$, 1.5 A, 50Hz. P.F 0.78 lag and 1410 rpm. The speed of motor ranging from 0 to 1500 rpm and DC link current are measured by tacho generator and hall-effect sensor, and both of them are then transformed to be a voltage ranging from 0 to 10 volts which will be the input of A/D card respectively. The symmetric chopper method that controls the IGBT to turn on and off is adopted to adjust the duty cycle of chopper under a certain fixed inverting firing angle at 130 degrees. This scheme enables the user to adjust the speed of the motor by the duty cycle of the chopper operating in PWM mode. The experimental results can be summarized as follows:

5.1. The power factor

The power factor of MSERS has been improved. That is, the power factor of MSERS is 0.7 lag but the power factor of SERS is only 0.5 lag as shown in Figure 6.
5.2 The current waveforms

The input line current waveforms by using the twelve-pulse converter with chopper shown in Fig. 7 and by using the twelve-pulse converter shown in Fig. 8 are distorted less than the current waveforms using the six-pulse converter shown in Fig. 9. It is found that the harmonics of the current of the MSERS are less than the SERS.

5.3 Step response of speed

From no-load condition to rated condition, the speed of motor can be kept constant by using fuzzy logic controller when the speed of motor ranges from 600 to 1350 rpm as shown in Fig. 10 and Fig. 11. From Figure 11 when 100% load is applied and release at the speed 1350 rpm, the fuzzy logic controller can keep the motor speed. From the experimental results obtained, the proposed MSERS with fuzzy logic controller can keep the motor speed to be constant at the speed ranging from 600 to 1350 rpm.
6. CONCLUSIONS

In conclusion, the modified slip energy recovery system using fuzzy technique based chopper has been shown. The power factor has been improved significantly and the harmonics of the current of the MSERS are less than that of SERS. In addition, the speed of the wound rotor induction motor can be controlled at the desired speed without steady-state error.

REFERENCES


Fig. 12 Step load 100% Applied at 1350 rpm