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Current Source Inverter Fed High Speed Permanent Magnet Brushless DC Motor

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ABSTRACT*:* A surface mounted PM motor with the ratings of 5 kW and 15000 rpm is applied for high speed drive applications such as machine tool. A much larger air gap, compared with that of the existing PM motors, is utilized to reduce the slot ripples and hence the resultant eddy current loss in the metallic sleeve that retains the permanent magnets, otherwise this loss would be objectionable at such high speeds. The motor is supplied from a quasi-current source inverter with the dc current controlled by a chopper and operated at a near unit power factor by the use of a simple position sensor-less control, to improve the motor efficiency.

I. INTRODUCTION

High speed motors are receiving increasing attentions in various applications such as machine tool and waveguide, because of the advantages of small size and light weight at the same power level.[1]
To realize high speed operation, high efficiency is required for the motor to suppress the heat generation in the motor, particularly in the rotor, because the substantial reduction in the size makes it difficult to dissipate the heat, and the rotor must be rugged enough to bear the strong stress resulted from high speed rotation. [2]Therefore simple structure is desirable for the rotor. Although squirrel cage induction motors have been widely used in various applications due to its relatively robust rotor structure and free maintenance, they are not suitable for rotating at speeds over several ten thousands rpm owing to the complex rotor structure. Moreover they have low efficiency because of the iron losses as well as the copper losses occurred in the rotor windings, which may generate too much heat in the rotor.[3] They have, however, rather poor power factor and low efficiency, compared with permanent magnet motors, due to the large effective air gap length for which large excitation current is required.

Having high efficiency, permanent magnet motors fed from inverters are becoming increasingly attractive in a wide variety of speed control applications of low and medium power range, particularly following the recent development in commercial high power density magnetic materials, such as neodymium iron boron *(NdFeB)* magnet.[4] Motors constructed of *NdFeB* magnets have the highest efficiency of any motor yet developed and hence are expected to find increasingly various applications.

Since the surface mounted PM motor produces a square wave of the air gap flux and a concentrated stator winding will have a trapezoidal induced EMF waveform, square wave currents are desirable for this type motors. As the required rated fundamental frequency for the motor is as high as 250Hz, a current controlled PWM voltage source inverter may not provide the satisfactory waveform considering the practical switching frequency of the power devices; lower than 20 kHz for IGBT's. On the other hand, a current source inverter can offer good voltage waveforms, but requires a large reactor to smooth the dc current. Moreover, no single module for a three phase current source inverter circuit is available, resulting in a bulky power circuit.[5]

To realize a compact power circuit that provides the desired current waveform, a quasi-current source inverter (QCSI) is employed for supplying the motor, which is consisted of a diode rectifier, a current controlling dc chopper and a voltage type inverter, Moreover, to improve the input power factor, the usually large electrolytic capacitorof the dc filter (C d) is replaced with a substantially reduced film capacitor, which is enabled by the appropriate current control of the chopper.[6] The elimination of the large capacitor also solves the rush current problem at starting, and therefore no rush current limiting element is required, further reducing the parts count.

II. BRUSHLESS DC MOTOR MODEL

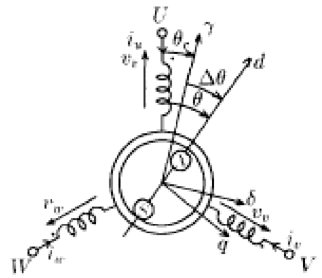

Fig 1 Analytical model of brushless motor

The fig. 1 shows an analytical model of brushless motor with a sinusoidal flux distribution , where d-q axis corresponds to the actual rotor position and γ-δ is the assumed rotor position with an angular error Δθ with respect to the actual rotor position.

$$\Delta\theta = \theta_c - \theta \tag{1}$$

The voltage equation, where Ra, La; armature winding resistance and inductance, K3; emf constant, i_u , i_v, i_w; line currents, v_u , v_v , v_w; phase and voltages and p isa derivative power

$$\begin{bmatrix} Vu \\ Vv \\ Vw \end{bmatrix} = \begin{bmatrix} Ra + PLa & PLa(2\pi/3) & PLacos(4\pi/3) \\ PLacos(4\pi/3) & Ra + PLa & PLacos(2\pi/3) \\ PLacos(2\pi/3) & PLacos(4\pi/3) & Ra + PLa \end{bmatrix} \begin{bmatrix} iu \\ iv \\ iw \end{bmatrix} + K3P \begin{bmatrix} \cos\theta \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix} \tag{2}$$

Without a position sensor, the actual rotor position is unknown, and an equivalent two-axis model based on the γ-δ axis should be obtained by applying the transformation matrix.

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$$\begin{bmatrix}\gamma \\ \delta\end{bmatrix} = \sqrt{2/3}\begin{bmatrix}\cos\theta c & \cos(\theta c - 2\pi/3) & \cos(\theta c + 2\pi/3 \\ -\sin\theta c & -\sin(\theta c - 2\pi/3) & -\sin(\theta c + 2\pi/3)\end{bmatrix}\begin{bmatrix}u \\ v \\ w\end{bmatrix} \quad (3)$$

As a result, the γ-δ axis voltage equation of the brushless motor and the generated.

$$\begin{bmatrix}v_\gamma \\ v_\delta\end{bmatrix} = \begin{bmatrix}R + PL & -L\theta \\ L\theta & R + PL\end{bmatrix}\begin{bmatrix}i\gamma \\ i\delta\end{bmatrix} + K_E\theta\begin{bmatrix}-\sin\Delta\theta \\ \cos\Delta\theta\end{bmatrix} \quad (4)$$

$KE=\sqrt{3/2}K_E{}^3$, $\theta= d\theta/dt$, $\theta=d\theta/dt$

$R = R_a$, $L = (3/2)L_a$

$$\tau = K_T i_\delta \cos\Delta\theta \quad (5)$$

The motor under assumptions that $\Delta\theta\equiv0$ and $\theta u=\theta$. It is noted here that the block of a $\gamma -$ axis component under the condition $i\gamma = 0$ is the same as that of the conventional dc motor.

III. QUASI- CURRENT SOURCE INVERTER

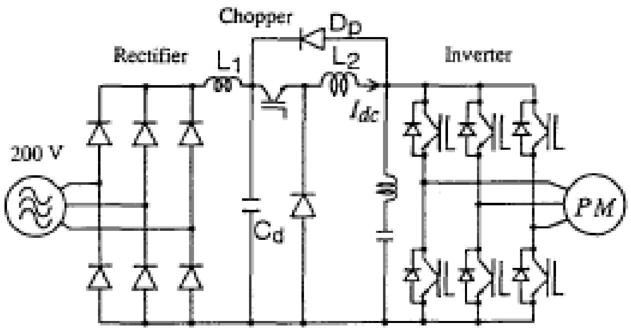

Fig.2 Circuit configuration for quasi- current source inverter

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IV. POWER CIRCUIT CONFIGURATION

As mentioned earlier, a current source inverter (CSI) is desirable for supplying the surface mounted PM motor because it produces square wave current which are well matched to the induced EMF waveform in the stator windings. A conventional CSI, however, needs a large reactor to smoothing the dc current, and diodes are also required to be connected in series with the switching devices without reverse blocking capability such as bipolar transistor, or IGBT. This leads to a bulky power circuit.[7] A quasi-current sourceinverter that realizes a compact power circuit is therefore employed. It is consisted of a rectifier, a current controlling step-down chopper with a small inductor, a diode for bypassing the power regenerated from the motor and a inverter that has the same construction as the voltage source inverter, as shown in Fig. 2 In addition, an LC tuned filter is employed across the dc link of the inverter side to attenuate the current ripple resulted from the chopping operation of the chopper. IGBT's were employed for the switching devices because of the superior switching characteristics over the other commercially available devices.[8] To improve the input power factor, the usually used large electrolytic capacitor is eliminated from the dc filter of the diode rectifier. This also solves the rush current problem at starting, and therefore no rush current limiting element is required, further reducing the parts count. As a result, a substantially reduced film capacitor of 40 pF is enough to absorb the possible power recovered from the motor. Although the elimination of the large capacitor results in a fluctuated dc voltage for the chopper, the influence of the fluctuation on the motor current can be avoided by carefully designing the current controller of the chopper. The inverter is controlled in such a way as to supply three phase rectangular current with a pulse width of 120" electrical degree to the motor, and the amplitude of the current is regulated by the step-down chopper. The switching instants are synchronized with the terminal voltages of the motor, which will be discussed in the following section.[9] During the switching operation and current commutation period thereafter in the inverter, diode Dp together

with the corresponding free- wheeling diodes of the inverter provide a path for the current; otherwise Dp is turned off. Therefore the diodes connected in series with the switching devices in a conventional CSI can be eliminated, and a module containing six switching device can be utilized, which contributes to the parts reduction. Moreover, during this period the motor current is no longer controlled by the chopper whereas the dc link voltage is applied to the motor. In the case of poor power factor operation of the motor, this period become long, resulting in a voltage source inverter operation. [10] It is therefore obvious that unit power factor operation is desirable for decreasing the period operated as a voltage source inverter and thus improving the voltage waveforms.

Sensor-Less Control Circuit

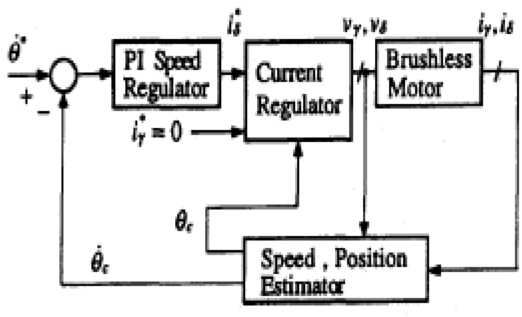

Fig. 3 Sensor less Control Block

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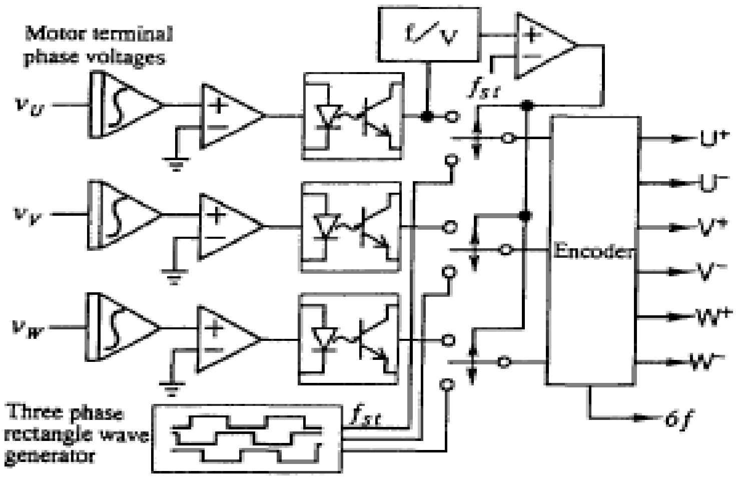
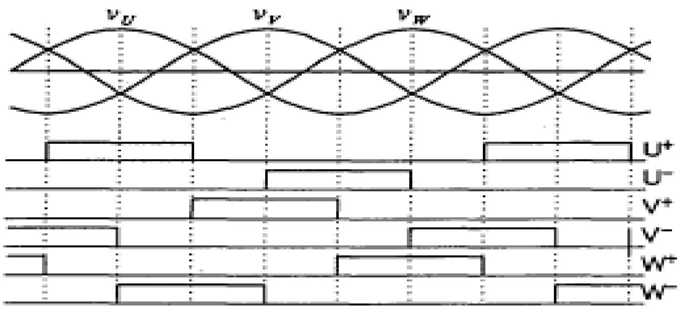


Fig .4 Sensor Less Control Circuit

PM motors require alternating stator currents to produce constant torque, and to control them the rotor flux position has to be identified. Rotor position information is used to manage the switching of the inverter to the phases of the stator current in correct sequence by a control circuit. It is, however, very difficult, if not impossible, to install a mechanical shaft position sensor at such high speed motor, besides the drawbacks of using a sensor as well documented in many literature. Therefore position sensor-less control of the motor is required.[11]
A simple sensor-less control method was employed in which the terminal

voltages of the motor are used to determine the switching instants of the inverter. Fig. 3 shows the control block diagram of the sensor-less control circuit, and Fig. 5 the switching timing chart of the inverter, which is performed by an encoder circuit. The objective of the control is to realize a unit power factor operation for the PM motor by forcing the currents in phase with the motor terminal voltages. The phase information of the voltages are detected by three comparators. Since the phase voltages may contain many switching noises, the correct phase information may not be obtained, particularly when the phase voltages are small at low speeds. For this reason, integrators are placed before the comparators as filters to improve control characteristic at low speeds. The insulation between the main power circuit and the controller is provided by photo- couplers instead of isolation amplifiers, because of its low cost. Since this control method uses the phase information of the terminal voltages to detect the position of the rotor, the motor must be started firstly. This may be accomplished by supplying a fixed low frequency (fst) current forcibly to the motor. After the motor speed exceeds this preset value sensor-less control is entered.



Current control
Fig.5 Switching time chart of the inverter

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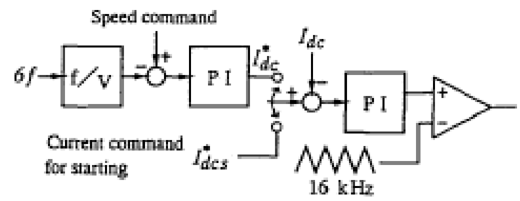

Fig.6 Speed control block diagram

The dc current is controlled by the IGBT chopper, which in turn controls the motor speed. A high switching frequency of 250Hz is used which reduced the size of the dc link reactor while keeping the current ripple small. Moreover the current ripple is further attenuated by the LC tuned filter connected across the dc link of the inverter side. Fig. 6 shows the speed control block diagram. The current command I_{dc}*is generated from the error signal between the commanded speed and the actual value through a PI controller. The motor speed signal is obtained by converting the frequency of the terminal voltages to a dc signal through a f N converter. At starting, an appropriate current command I_{dc}*is given to the control circuit which performs constant current control. Therefore the motor can be started softly without over currents[11-15].

No- Load Loss

The iron losses in the stator, the SUS sleeve of prototype A, and the mechanical losses of the FRP rotor including the wind age and friction loss in the bearings. The stator loss was measured by supplying the stator with the inverter under a constant voltage/frequency ratio to maintain a constant flux in the stator, and a silicon steel laminated cylinder was inserted into the stator so that the same effective gap length as in the case of PM rotor is resulted. The figure shows clearly that the iron loss in the SUS sleeve becomes larger than the other losses when the speed and that the mechanical losses increase drastically with rotor speed. The increase in the mechanical losses is mainly attributed to the sudden increase in the wind age loss with the speed.

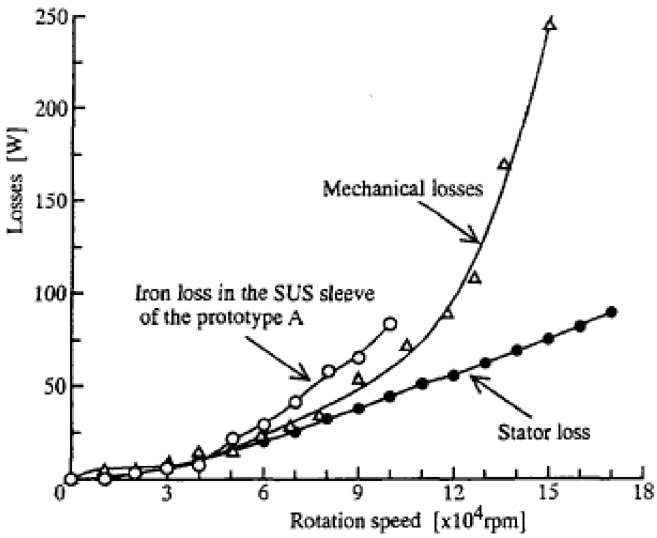

Fig.7 Separated no-load losses various rotor speed

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Motor efficiency various load torque

Load test was carried out by coupling a disk on the shaft and placing it in a external controlled magnetic field. When the disk rotates with the motor, eddy current is generated in the disk and in turn braking torque is exerted on the shaft. Fig. I1 shows the efficiencies of the three prototypes versus the load torque sat rotor speed, which is the allowable maximum speed because of the mechanical resonance of the shaft with the brake disk. The efficiencies of the motor with a FRP sleeve retained rotor are higher than 90% with a maximum value of 94.1%, while the maximum efficiency of prototype A with thicker SUS sleeve is 88.5%..

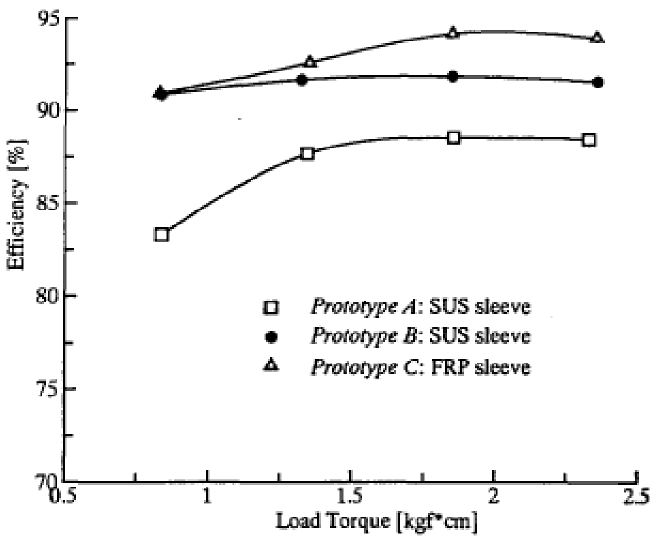

Fig.8 motor efficiency various load torque

V. CONCLUSION

A super high speed PM motor drive system with the ratings of 5 kW and 15000 rpm has been presented. The use of a relatively large air gap, compared with the present PM motors, can substantially reduce the slot ripples and hence the resultant eddy current loss in the metallic sleeve. As a result, high efficiency of above 90%can be realized with the motor that has a thin taintless steel leave suitable for operation. The new quasi-current source inverter for supplying the motor described in this paper embodies the following features The large electrolytic capacitor of the rectifier dc filter is eliminate by the current control of the chopper, realizing high input power factor and solving the rush current problem. The large dc reactor used in a conventional current source inverter is replaced by a step-down chopper with a small reactor, which provides fast response or current control. The diode required for a conventional current source inverter constructed of switching devices without reverse blocking capability, such as IGBT's are also eliminated by using a power by- pass diode. Therefore a single module containing six switching devices can be employed reducing the parts count. Near the power factor of the PM motor is realized by the use of a single sensor-less control circuit improving the efficiency of the motor and reducing the VA capacity of the inverter.

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