論 文
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# 병렬권선 방식에 의한 SRM의 부하전류분담

# A New Current Sharing Strategy of SRM Using Parallel Winding Method

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**Abstract** - The switched reluctance motor(SRM) has a considerable potential for industrial applications because of its high reliability as a result of the absence of rotor windings. In some applications with SRM, a parallel switching strategy is often used for cost saving, increasing of current capacity and system reliability.

This paper proposes a new parallel switching strategy of SRM using parallel winding. While conventional parallel switching devices are connected in a phase winding, power devices are connected in the parallel windings wound in each pole of stator in the proposed method. Paralleling strategy for current sharing in the proposed method can be easily determined without considerations of any nonlinear characteristics of power devices such as conduction resistance, threshold voltage and gain factor. The proposed paralleling strategy is verified by the mathematical analysis and experimental results.

**Key words** : SRM, Parallel switching, Current sharing, Parallel winding method

## I. INTRODUCTION

The inherent simplicity, ruggedness, and low cost of a switched reluctance motor(SRM) make it a viable candidate for various general purpose adjustable speed applications[1-4]. The applications with SRM drive are much increasing due to high degree reliability resulting from simple power electronic drive circuit and high fault tolerance of the converter.

In some applications with SRM, parallelling strategy is often used for cost saving, high current capacity and high reliability of the system. Paralleling system helps to reduce conduction losses, system cost and size of power devices[5-7]. General paralleling strategy of SRM uses parallel switching method with parallel connected power devices in a phase winding.

Whenever devices are operated in parallel, some considerations should be given to the current sharing between devices to ensure that the individual units are operated within their limits. However, in the general parallel switching method of SRM, unbalanced currents resulting from parameter mismatch between parallel power devices and gate driver must be considered. For the suppression of unbalanced current in an appreciate range, additional sharing resistor, dynamic current balancing transformer or active feedback to the driver are required in a general parallel switching method of SRM[8].

This paper proposes a new paralleling strategy using parallel winding method. Since the proposed parallel winding method uses seperate windings for a phase winding, the sharing characteristics of parallel currents depends on electrical parameters of each windings. With the mathematical model of the parallel wound SRM, unbalanced current is analyzed and balancing strategy is introduced.

The proposed paralleling strategy is verified by the mathematical analysis and experimental results.

## II. PARALLELLING STRATEGY USING PARALLEL WINDING METHOD

### A. Conventional Parallel Switching Method

The specifications of commercial power switches such as IGBT, FET and power Transitor have generally regular power densities. However, in practical applications, power densities of load are various, and higher than that of the power density of power semiconductors in some cases. In these cases, the operating region is over the SOA(safety operating area) of general power devices. Especially, higher current applications require sufficient conducting current capacity of power semiconductors. For these reasons, paralleling strategy is widely used in

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practical application due to cost saving and high degree reliability.

Fig. 1 shows conventional parallel switching method of SRM drive. The power devices are connected in a phase winding for the load sharing.

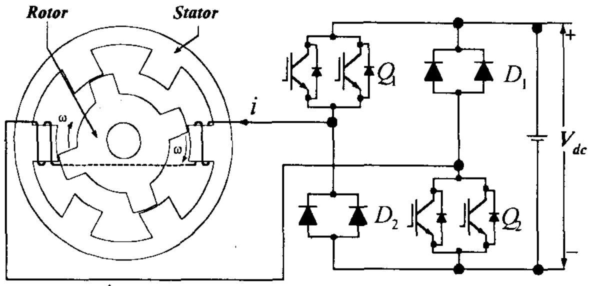



**Fig. 1** Conventional parallel switching method for SRM

However, each power devices and gate driver have different nonlinear characteristics. Unbalanced currents are caused by the mismatch of device's parameter, gate driver and power circuit[8]. Especially, some parameter such as switching-on resistance, threshold voltage and gain are very sensitive. For the precise current sharing in a parallel switching method, voltage regulated gate driver and auxiliary circuits for parameter matching are required.

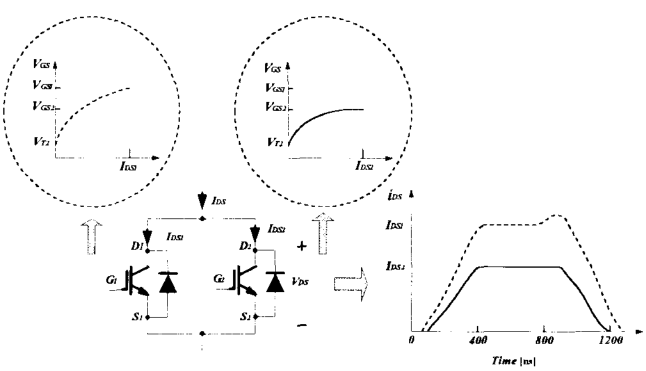



**Fig. 2** Unbalanced current according to transfer gain factor and threshold voltage mismatch

Fig. 2 shows the characteristics of current sharing in parallel switching method with different transfer characteristics of active region for gain and threshold voltage of power devices.

In this case, load current is concentrated in a power device with higher gain and lower threshold voltage, and the result shows current unbalance in the parallel switches. Though unbalanced parallel currents are in SOA of each power devices, unbalanced current and transition energy are significant problem in applications where conduction losses dominate the thermal design. For this reason, series resistor may be attached for correcting of unbalanced current in some application. Since electrical characteristics of power devices were inherent properties, gate driver's parameters must be adjusted for current balancing in parallel paths. Moreover, the transfer characteristics of gain factor and threshold voltage of power devices can vary with environmental temperature.

### B. Proposed Parallel Winding Method

This paper proposes a new current sharing method using parallel windings.

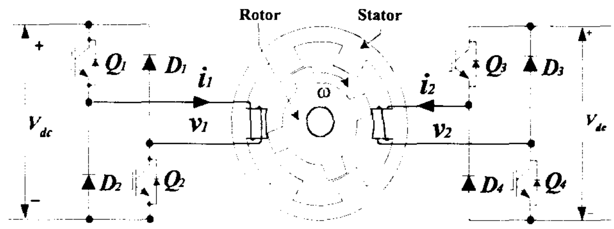



**Fig. 3** SRM drive system with the parallel winding method

Fig. 3 shows basic concept of the proposed parallel winding method. While general parallel switching devices are connected in a single phase winding, power devices are connected in each parallel windings in the proposed method as shown in Fig. 3.

Current sharing characteristics of the proposed parallel wound SRM depends on electrical parameters of each winding regardless of nonlinear gain or threshold voltage. Furthermore, electrical parameters of SRM can be precisely adjusted in practical applications.

## III. UNBALANCE CURRENT ANALYSIS IN THE PARALLEL WOUND SRM

As stated previously, current sharing characteristics of the proposed parallel winding method depends upon load system instead of the power devices. Load currents of each power devices are dominated by the discrete single winding parameters. For the analysis of current sharing characteristics in the proposed parallel wound SRM, mathematical model is derived from equivalent circuit of parallel wound SRM.

The instantaneous voltage equation derived by equivalent circuit of SRM can be expressed as follows.

$$V = Ri + \frac{d\lambda}{dt}, \quad (1)$$

where, $V$ : applied terminal voltage,

$i$ : phase current,

$R$ : winding resistance,

$\lambda$ : linkage flux,

Differential of SRM linkage flux can be expressed as follow.

$$\frac{d\lambda}{dt} = L\frac{di}{dt} + i\omega\frac{dL}{d\theta}, \quad (2)$$

where, L : phase inductance,

$\omega$ : angular velocity,

$\theta$ : angular position,

The first term of right side is dominant term during transient, but to be zero in steady state. The last term of right side is dominant term in steady state. With the assumption of steady state, the phase current can be derived from (2).

$$i = K_e\frac{d\lambda}{dt}, \quad (3)$$

where, $K_e = \frac{1}{\omega}\frac{d\theta}{dL}$,

Fig. 4 shows the graphical analysis of applied voltage and phase current in general operating region. The subscript 'A', 'B' and 'C' denote the operating modes such as exciting, wheeling and demagnetizing mode, respectively. In single pulse switching, exciting and demagnetizing mode are used alternatively while exciting, wheeling and demagnetizing mode are used in PWM switching method.

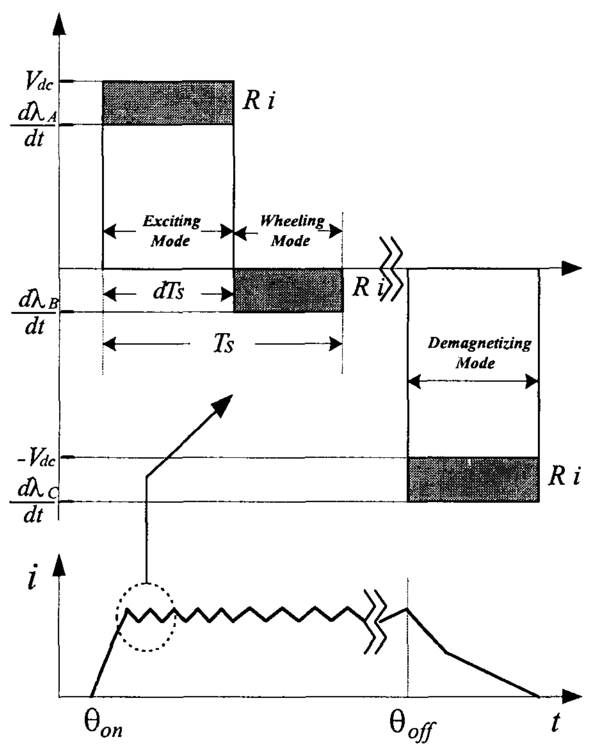



**Fig. 4** The graphical analysis of operating mode in PWM switching

The main focus of the proposed paralleling strategy is to ensure that the individual devices are operated within their current limits.

Since the peak currents are presented on exciting mode in each switching strategy, only exciting mode is considered for the practical current sharing of the proposed parallel winding method. With consideration of voltage drop on power devices and actual parameter mismatch, the equivalent circuit during exciting mode is shown in Fig. 5.

In each operating modes, the differential term of linkage flux can be expressed as a function of applied voltage and voltage drops on the winding and power devices. With consideration of voltage drops in power devices, differential of linkage flux can be derived from (2) as follows in exciting modes.

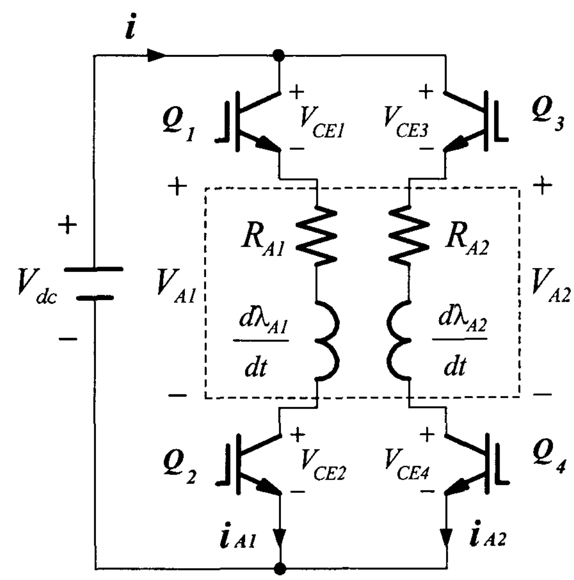



**Fig. 5** The equivalent circuit of parallel wound SRM

$$\frac{d\lambda_{A1}}{dt} = V_{dc} - (V_{CE1} + V_{CE2}) - R_{A1}i_{A1},$$
$$\frac{d\lambda_{A2}}{dt} = V_{dc} - (V_{CE3} + V_{CE4}) - R_{A2}i_{A2}, \quad (4)$$

where, $V_{CE}$ is a voltage drop on the power switch.

The subscript of '1' and '2' denotes each parallel windings. In an ideal case that winding resistance and voltage drops on power devices are the same, differential linkage fluxes of each parallel windings are the same due to the same supply voltage $V_{dc}$.

For the analysis of unbalanced current in steady state, transient terms of differential linkage flux are assumed to be zero. Therefore voltage and resistance differences between the parallel windings are

$$\Delta V = (V_{CE1} + V_{CE2}) - (V_{CE3} + V_{CE4}), \quad (5)$$

$$\Delta R = R_{A1} - R_{A2}. \quad (6)$$

From (5) and (6), applied voltage and winding resistance of the other winding can be expressed as follows.

$$V_{A1} = V_{A2} - \Delta V, \quad (7)$$

$$R_{A1} = R_{A2} - \Delta R. \quad (8)$$

From (2) and (8), unbalance current of the proposed parallel winding method can be derived as follows.

$$i_{A2} = i_{A1} - \frac{\Delta V i_{A1} - \Delta R \cdot i_{A1}^2}{V_{A2} + \Delta V - \Delta R\, i_{A1}} \quad (9)$$

Since phase current is dominated by the differential linkage flux in steady state, shared currents by the proposed parallel winding method are the same in ideal case. In practical case, the unbalanced term by the voltage difference is very smaller than the applied voltage so that the current sharing difference due to the voltage difference is neglectable. Also the winding resistance difference can be corrected in the motor manufacturing stage. Therefore, the current sharing ratio of the proposed parallel winding method can be precisely adjusted without the effect of nonlinear characteristics of power devices.

Fig. 6 shows the analytical result of the percent unbalance current between parallel windings. In practical case, the unbalance current can be suppressed under 5[%] in the proposed parallel winding.

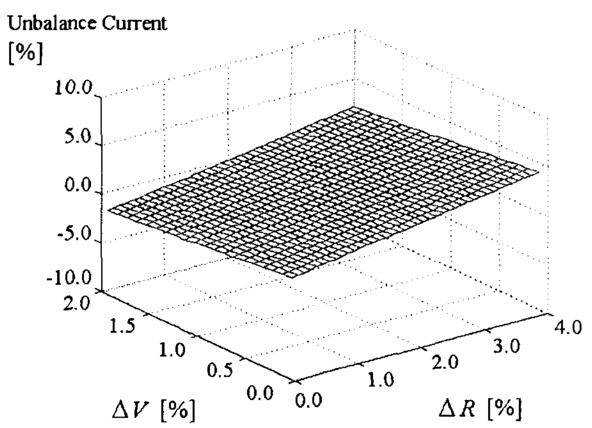



**Fig. 6** The unbalance factor of the proposed parallel winding SRM

## IV. EXPERIMENTAL RESULTS AND CONSIDERATIONS

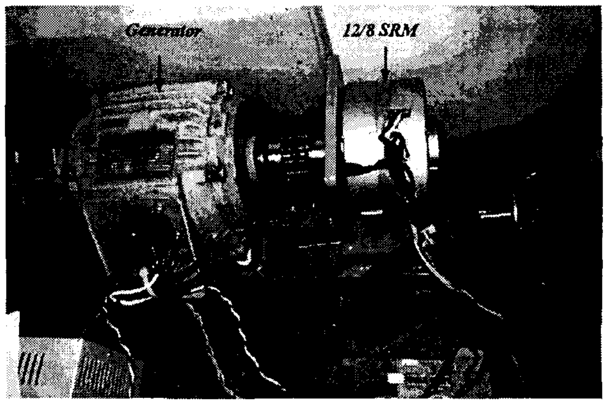



**Fig. 7** Experimental test system with 12/8 SRM and generator

7 shows the 12/8 SRM and load system used in the experimental test. For the practical test, different kind of power devices are used.

**Table 1** The specifications of target SRM

| | | | |
|---|---|---|---|
| The number of stator poles | 12 | The number of rotor poles | 8 |
| Stator arc | 16° | Rotor arc | 20° |
| Outer diameter of stator | 132.0 mm | Outer diameter of rotor | 72.5 mm |
| Air gap | 0.2 mm | Length of core | 28.0 mm |
| Number of turn per phase | 140 turn | Diameter of conductor | 0.52 mm |
| Winding resistance | 2.5Ω | Rated speed | 3000 rpm |

Table 1 shows the specifications of target SRM. Fig. 8 shows the block diagram of the overall control system. The speed signal from the encoder equipped SRM was captured for the speed control and switching pattern generation. The general PI controller was used for speed control. For the experimental verification, one phase winding was connected by the proposed parallel winding method and the other phases have single winding structure.

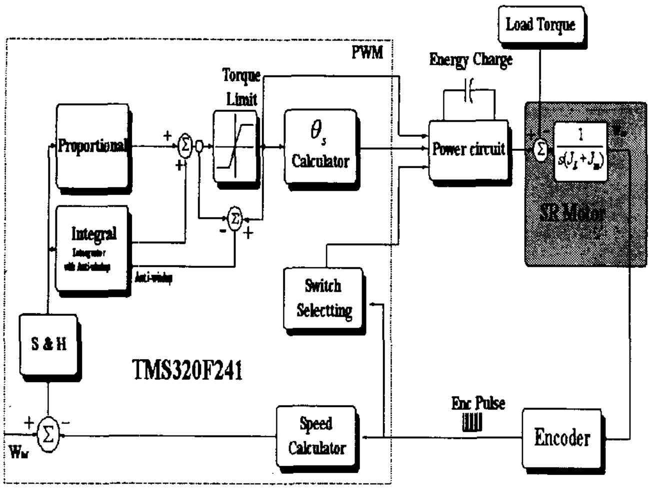



Fig. 8 Configuration of the overall controller

For the experiment, the winding of phase B is re-winded with parallel winding method. Fig. 9 and Fig. 10 shows the current sharing characteristics of the proposed parallel winding method in case of single pulse switching at 3000rpm. The upper $i_A$ denotes phase 'A' current of single winding and $i_{B1}$ and $i_{B2}$ are currents of parallel winding respectively. Though shared currents of parallel windings have small error due to the inductance difference between parallel connected windings. In the steady flat-top current region, magnitudes of shared phase current $i_{B1}$ and $i_{B2}$ are same as analyzed and suppressed under rated of each power devices. The difference of $i_A$ and $i_{B1}+i_{B2}$ is by impedance error of phase A and parallel re-winded phase B.

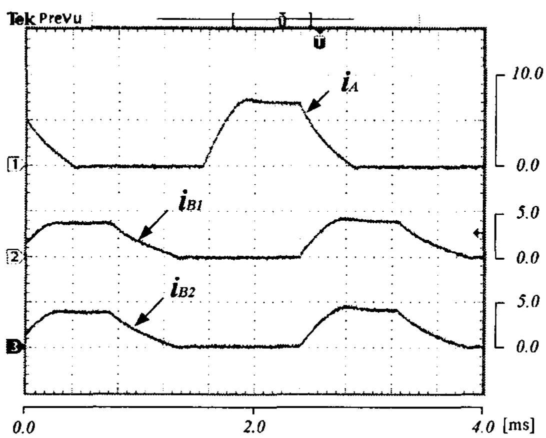
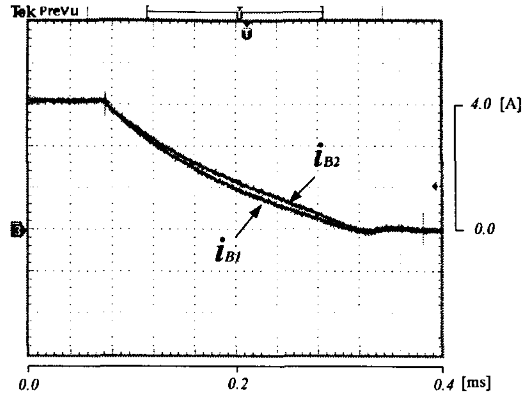
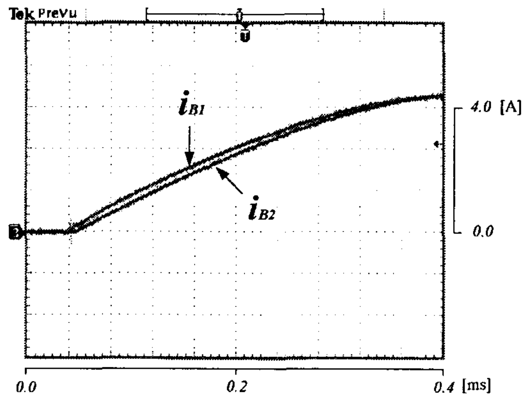



Fig. 9 Current waveform in parallel windings with single pulse switching




(a) Transient currents in exciting mode




(b) Transient currents in demagnetizing mode

Fig. 10 Currents waveform in transient region with single pulse switching

Although current waveforms of each parallel windings are small different due to the inductance error resulting from manual winding in the laboratory, the peak currents is under rated current of each power devices and stable parallel operation is possible.

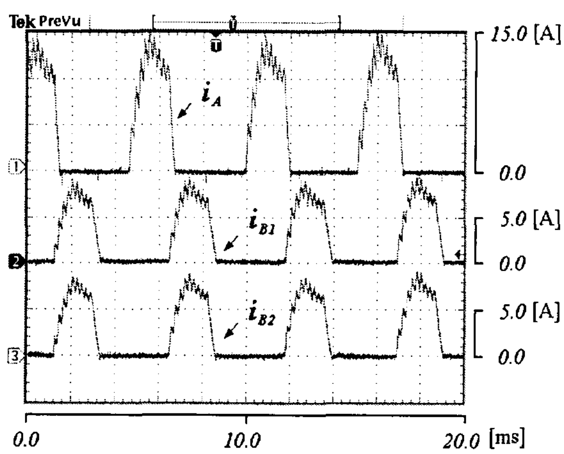
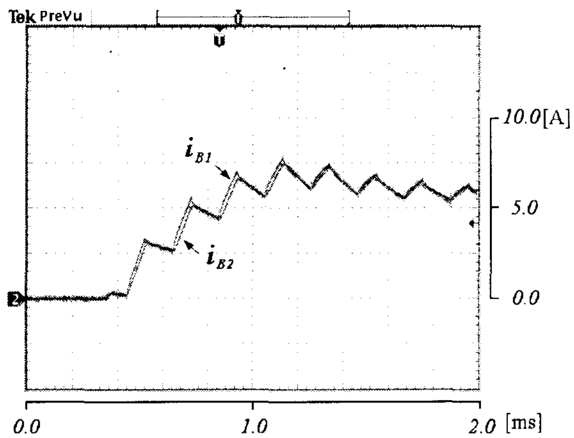


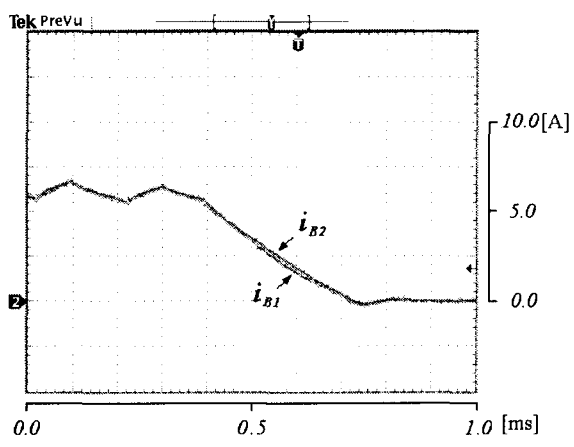

Fig. 11 Characteristics of current sharing in parallel windings with PWM mode

Fig. 11 and Fig. 12 show the experimental result in case of PWM switching mode at 1800rpm. At the starting point of exciting mode, shared currents of parallel windings have a small difference due to the difference of electrical characteristics such as inductance and resistance. However, in the steady state, the difference component of shared windings is dramatically decreased.

The experimental results show that the proposed parallel winding method is effective for current sharing and stable parallel strategy is possible without any additional circuits.




(a) Transient currents in exciting mode




(b) Transient currents in demagnetizing mode

**Fig. 12** *Currents waveform in transient region with PWM pulse switching*

## V. CONCLUSIONS

The general parallel switching method is widely used in practical system due to the cost and reliable current sharing in high current applications. However, each power devices and gate driver connected parallel have different nonlinear characteristics. Current unbalance in parallel switching method are from the mismatch of device parameter's, gate driver and power circuit.

This paper investigates a parallel winding method for stable current sharing of SRM. For the exact current sharing with conventional parallel switching method, voltage regulatable gate driver and auxiliary circuits for devices parameter's matching are to be required. However, the characteristics of current sharing in the proposed parallel winding depend on the electrical parameters of SRM. And the electrical parameters of each parallel windings can be precisely calculated and adjusted in application stage. With the mathematical analysis of the proposed parallel winding method, the effect of power devices and electrical parameters of SRM was analyzed. In the practical parallel winding system, voltage error is very smaller than applied voltage, and winding resistance difference can be corrected in the motor manufacturing stage. Therefore, current sharing ratio of the proposed parallel winding method can be precisely adjusted without the effect of nonlinear characteristics of power devices.

The experimental results show the verification of the proposed parallel winding method. It makes possible to apply for a high power drive with current shared operation.

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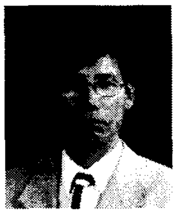

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