<table>
<thead>
<tr>
<th>Title</th>
<th>Relationship of parallel model and series model for permanent magnet synchronous motors taking iron loss into account</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Urasaki, Naomitsu; Senjyu, Tomonobu; Uezato, Katsumi</td>
</tr>
<tr>
<td>Citation</td>
<td>IEEE Transactions on Energy Conversion, 19(2): 265-270</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2004-06</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/20.500.12000/4628">http://hdl.handle.net/20.500.12000/4628</a></td>
</tr>
<tr>
<td>Rights</td>
<td>©2004 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.</td>
</tr>
</tbody>
</table>
Relationship of Parallel Model and Series Model for Permanent Magnet Synchronous Motors Taking Iron Loss Into Account

Naomitsu Urasaki, Member, IEEE, Tomonobu Senjyu, Member, IEEE, and Katsumi Uezato

Abstract—This paper investigates the relationship of parallel model and series model for permanent magnet synchronous motor taking iron loss into account. The expressions of flux linkage, terminal voltage, and electromagnetic torque are compared. It follows from the investigation that the parallel and series models are mathematically the same. In addition, the properties of the models are exhibited. The parallel model is superior in understanding the physical meaning to the series model. The series model is superior in low order of the state variables to the parallel model.

Index Terms—Iron loss resistance, parallel model, permanent magnet synchronous motor, series model.

I. INTRODUCTION

As the employment of vector-controlled ac motors, especially induction motor and permanent magnet synchronous motor (PMSM), has become standard in industrial drives, the improvement of ac motor drives has been an important issue. Traditionally, vector control strategies have been performed under the assumption that there is no iron loss in motors. However, since the iron loss influences the flux linkage and electromagnetic torque in ac motors, it has been necessary to compensate the influence of the iron loss in vector control strategies. For this reason, several authors have made an attempt to consider the iron loss in vector-controlled ac motor drives.

In those studies, equivalent circuits with an iron loss resistance are utilized. From a modeling point of view, they can be classified as either parallel or series type. The parallel model inserts an iron loss resistance in the equivalent circuit with the parallel fashion and it is employed in [1]–[5]. By contrast, the series model inserts an equivalent iron loss resistance in the equivalent circuit with the series fashion and it is employed in [6]–[9]. In this situation, however, the relationship between the parallel and series models has not been clarified.

It is the purpose of this paper to reveal the relationship of the two types of model for PMSM. In the first phase, the formulations of both the parallel and series models are illustrated. In the second phase, the expressions of flux linkage, terminal voltage, and electromagnetic torque are compared. In addition, the properties of both parallel and series models are exhibited.

II. MATHEMATICAL FORMULATION OF PMSM TAKING IRON LOSS INTO ACCOUNT

In the synchronous reference frame $(d-q)$, the voltage equation for PMSM is expressed as [10]

$$
\begin{align*}
    v_d &= R_i i_d + p \omega_m \Psi_d - \omega_d \Psi_q \\
    v_q &= R_i i_q + p \omega_m \Psi_q + \omega_d \Psi_d
\end{align*}
$$

(1)

where the first term in the right-hand side represents the voltage drop due to the armature resistance $R$, and the second and third terms represent the transformer electromagnetic-force (emf) and speed emf, respectively.

From an expression of the $d-q$ axes flux linkages ($\Psi_d$, $\Psi_q$), it is possible to classify mathematical models for PMSM taking iron loss into account into two main categories (i.e., parallel or series type). In this section, expressions of flux linkage for the two types of model are explained.
A. Parallel Model

Fig. 1 shows the $d-q$ axes equivalent circuits for PMSM which are traditionally applied to consider iron loss [2]. In this circuit, an iron loss resistance $R_i$ is inserted in parallel with the magnetizing branch. Thus, the $d-q$ axes line currents ($i_d$, $i_q$) are divided into the iron loss currents ($i_{dL}$, $i_{qL}$) and magnetizing currents ($i_{dM}$, $i_{qM}$).

The iron loss $P_i$ arises from the iron loss resistance $R_i$ and is expressed as

$$P_i = R_i (i_{dL}^2 + i_{qL}^2).$$

In steady-state condition, the iron loss currents ($i_{dL}$, $i_{qL}$), illustrated in Fig. 1, are expressed as

$$i_{dL} = -\frac{\omega_c \Psi_d}{R_i},$$

$$i_{qL} = \frac{\omega_c \Psi_q}{R_i}.$$  \hspace{1cm} (3)

It is noted that since the $d-q$ axes magnetizing currents ($i_{dM}$, $i_{qM}$) are dc quantities in steady-state condition, the transformer emfs ($L_p i_{dM}$, $L_p i_{qM}$) become zero. Thus, these components do not appear in (3). As a result, the iron loss can be rewritten as

$$P_i = \frac{\omega_c^2 (\Psi_d^2 + \Psi_q^2)}{R_i}.$$  \hspace{1cm} (4)

Supposing the iron loss resistance $R_i$ is constant, (4) corresponds to only an eddy current loss, because $P_i$ is proportional to the product of the square of electrical angular velocity $\omega_c^2$ and the square of flux linkages ($\Psi_d^2 + \Psi_q^2$). For practical purposes, in order to include a hysteresis loss into $P_i$, the iron loss resistance $R_i$ is usually treated as a function of the electrical angular velocity $R_i(\omega_c)$ [3].

The flux linkage equation for the parallel model is given as

$$\Psi_d = L_i i_{dM} + K_e, \quad \Psi_q = L_i i_{qM}$$  \hspace{1cm} (5)

where $K_e$ corresponds to a permanent magnet flux linkage [2].

B. Series Model

A series type mathematical model for PMSM taking iron loss into account is derived from a magnetic coupling between an armature circuit and eddy current circuit [8]. In this model, the iron loss $P_i$ arises from the resistance $R_3$ of the eddy current circuit (see the Appendix). In steady-state condition, from (A.2) in the Appendix ($p \Psi_{3d} = 0$, $p \Psi_{3q} = 0$), the iron loss $P_i$ is expressed as

$$P_i = R_3 \left( i_{dL}^2 + i_{qL}^2 \right)$$

$$= \frac{\omega_c^2 (\Psi_{3d}^2 + \Psi_{3q}^2)}{R_3}.$$  \hspace{1cm} (6)

It is noted that the $d-q$ axes flux linkages ($\Psi_{3d}$, $\Psi_{3q}$) for the eddy current circuit are equal to the flux linkages ($\Psi_d$, $\Psi_q$) for the armature circuit when (A.6) in the Appendix is presumed. The flux linkage equation for the series model is given as follows [8]:

$$\Psi_d = \Psi_{ds} + \Psi_{dM}$$

$$\Psi_q = \Psi_{qs} + \Psi_{qM}$$

$$\Psi_{ds} = L_m i_d + K_{erm}$$

$$\Psi_{qs} = L_m i_q$$

$$\Psi_{dM} = -\frac{R_m \omega_c}{R_m} (i_d + \frac{K_e}{L})$$

$$\Psi_{qM} = -\frac{R_m \omega_c}{R_m} (i_q + \frac{K_e}{L}).$$  \hspace{1cm} (7) \hspace{1cm} (8) \hspace{1cm} (9)

The equivalent iron loss resistance $R_m$, equivalent armature inductance $L_m$, and equivalent emf constant $K_{erm}$ are defined as follows:

$$R_m = \frac{\omega_c^2 L^2}{R_3^2 + \omega_c^2 L^2}$$  \hspace{1cm} (10)

$$L_m = \frac{R_3^2}{R_3^2 + \omega_c^2 L^2}$$  \hspace{1cm} (11)

$$K_{erm} = \frac{R_3^2}{R_3^2 + \omega_c^2 L^2} K_e.$$  \hspace{1cm} (12)

The details of the above expression of the flux linkage for the series model are explained in the Appendix. Since the expression of the flux linkage for the series model is described in terms of the line currents ($i_d$, $i_q$), the $d-q$ axes equivalent circuits become series fashion as shown in Fig. 2. As can be seen from Fig. 2, added speed emfs appear in the equivalent circuit. The
effects of the iron loss on the armature circuit are reflected by these speed emfs. It is noted that the series model shown in Fig. 2 is expressive of only the armature circuit of PMSM. Thus, the iron loss cannot be obtained directly from this equivalent circuit, because the iron loss in the series model occurs in the eddy current circuit (see the Appendix). Nevertheless, since the series model includes the effect of the iron loss, it suffices for the vector-control strategies taking iron loss into account. As proved later, the iron loss in the eddy current circuit can be represented by using the quantities of the armature circuit.

III. RELATIONSHIP OF FLUX LINKAGE FOR PARALLEL AND SERIES MODELS

In this section, the expressions of the flux linkage are mathematically developed and the relationship of the two types of flux linkage is investigated. In these mathematical developments, the following assumption is introduced. Both the resistances $R_i$ and $R_3$ are much greater than the armature reactance ($\omega_L L$). In other words, the following relations are satisfied:

$$\left(\frac{\omega_L L}{R_i}\right)^2 \ll 1 \quad \text{and} \quad \left(\frac{\omega_L L}{R_3}\right)^2 \ll 1.$$  \hspace{1cm} (13)

A. Flux Linkage Equation for Parallel Model

From (3) and (5), the $d-q$ axes magnetizing currents ($i_{dm}$, $i_{qm}$) are expressed as follows:

$$i_{dm} = i_d - i_{id} = i_d + \frac{\omega_L L}{R_i} \left( i_q - \omega_L L i_{id} \right),$$  \hspace{1cm} (14)

$$i_{qm} = i_q - i_{iq} = i_q - \frac{\omega_L L}{R_i} \left( i_{id} + \frac{K_e}{L} \right).$$  \hspace{1cm} (15)

Substituting (15) into (14) eliminates the $q$-axis magnetizing current $i_{qm}$ in (14) as

$$i_{dm} = i_d + \frac{\omega_L L}{R_i} \left\{ i_q - \frac{\omega_L L}{R_i} \left( i_{id} + \frac{K_e}{L} \right) \right\}.$$  \hspace{1cm} (16)

Transforming the term ($-\left(\frac{\omega_L L}{R_i}\right)^2 i_{dm}$) in the right-hand side into the left-hand side gives

$$\left\{ 1 + \left(\frac{\omega_L L}{R_i}\right)^2 \right\} i_{dm} = i_d + \frac{\omega_L L}{R_i} \left( i_q - \frac{\omega_L K_e}{R_i} \right).$$  \hspace{1cm} (17)

Finally, applying the relation indicated in (13) to (17) gives the $d$-axis magnetizing current expressed in terms of the line current ($i_d$, $i_q$) as

$$i_{dm} \simeq i_d + \frac{\omega_L L}{R_i} \left( i_q - \frac{\omega_L K_e}{R_i} \right).$$  \hspace{1cm} (18)

In a similar way, the $q$-axis magnetizing current can be expressed as

$$i_{qm} \simeq i_q - \frac{\omega_L L}{R_i} \left( i_d + \frac{K_e}{L} \right).$$  \hspace{1cm} (19)

Substituting (18) and (19) into (5) yields the flux linkage equation described in the form of

$$\Psi_d \simeq L_{id} i_d + K_e + \frac{\omega_L L}{R_i} L_{iq},$$
$$\Psi_q \simeq L_{iq} - \frac{\omega_L L}{R_i} (L_{id} + K_e).$$  \hspace{1cm} (20)

B. Flux Linkage Equation for Series Model

Applying (13) to (10) simplifies the expression of the equivalent iron loss resistance $R_m$ as

$$R_m = \frac{\left(\frac{\omega_L L}{R_i}\right)^2 R_3}{1 + \left(\frac{\omega_L L}{R_i}\right)^2} \simeq \frac{\omega_L^2 L^2}{R_3}.$$  \hspace{1cm} (21)

Applying (13) to (11) simplifies the equivalent armature inductance $L_m$ as

$$L_m = \frac{1}{1 + \left(\frac{\omega_L L}{R_i}\right)^2} L \simeq L.$$  \hspace{1cm} (22)

In a similar way, the equivalent emf constant $K_{em}$ indicated in (12) is simplified as

$$K_{em} \simeq K_e.$$  \hspace{1cm} (23)

Thus, substituting (21) to (23) into (7) to (9) results in the flux linkage equation described in the form of

$$\Psi_d \simeq L_{id} i_d + K_e + \frac{\omega_L L}{R_i} L_{iq},$$
$$\Psi_q \simeq L_{iq} - \frac{\omega_L L}{R_i} (L_{id} + K_e).$$  \hspace{1cm} (24)

C. Comparison of Flux Linkage for Two Types of Model

It can be concluded from the following two points of view that the iron loss resistance $R_i$ and the resistance $R_3$ of the eddy current circuit are identical.

1) The iron loss $P_i$ arises from an added resistance. The resistance corresponds to $R_i$ in the parallel model and $R_3$ in the series model, respectively.

2) From (4) and (6), the forms of the iron loss $P_i$ for two types of model are the same. Furthermore, the iron loss $P_i$ corresponds to only eddy current loss as long as both the resistances $R_i$ and $R_3$ are constant.

From the sameness of the resistances, (20) is identical to (24). Thus, the expressions of $d-q$ axes flux linkages ($\Psi_d$, $\Psi_q$) for the parallel and series models are mathematically the same. In other words, expressing the magnetizing currents ($i_{dm}$, $i_{qm}$) with the line current ($i_d$, $i_q$) as shown in (18) and (19) and replacing the term ($\omega_L^2 L^2/R_i$) with the symbol $R_m$, where $R_i = R_3$, convert the expression of the flux linkage for the parallel model into that for the series model.

The validity of the relations indicated in (13) will be confirmed. Fig. 3(a) shows the iron loss resistance $R_i$ versus rotor speed $N_r$ for a 160-W PMSM [11]. The specifications of the PMSM are listed in Table I. As can be seen from Fig. 3(a), the iron loss resistance $R_i$ is almost proportional to the rotor speed $N_r$. The linear characteristic of the iron loss resistance qualitatively agrees with the results obtained in the literature [4], [5]. Fig. 3(b) shows the square of impedance ratio ($\omega_L^2 L^2/R_i$) versus rotor speed $N_r$. The ratio is calculated with using the electrical angular velocity $\omega_e$ [rad/s] $(= (2\pi/60)P N_r [rpm])$, armature inductance $L[H]$ listed in Table I, and iron loss resistance $R_i[O]$ shown in Fig. 3(a). As can be seen from Fig. 3(b), the ratio is much less than 1 (order of the ratio is $10^{-4}$) over the wide speed range. Furthermore, similar results can be obtained from other
The voltage equation for the parallel model is intuitively understandable (i.e., it is seen that the first, second, and third terms correspond to the voltage drop due to the armature resistance \( R_a \), transformer emf, and speed emf, respectively. However, the parallel model has the disadvantage of increase of state variables [i.e., the magnetizing currents \( i_{dm}, i_{qm} \]). In addition, the magnetizing currents should be estimated because they cannot be obtained directly.

### B. Voltage Equation for Series Model

Substituting (7) to (9) into (1) yields the voltage equation described in the form of

\[
\begin{align*}
\nu_d &= (R + R_m) i_d + p \left( L_m i_d + \frac{R_m K_e}{\omega_e} i_q \right) - \omega_e \left( L_m i_q - \frac{R_m K_e}{\omega_e} i_d \right) \\
\nu_q &= (R + R_m) i_q + p \left( L_m i_q + \frac{R_m K_e}{\omega_e} i_d \right) + \omega_e \left( L_m i_d + K_e i_m \right)
\end{align*}
\] (26)

where \( L_m \simeq L \) and \( K_e \simeq K_e \). The series model has the advantage that there is no need to estimate the magnetizing currents \( (i_{dm}, i_{qm}) \). However, it is difficult to intuitively understand physical meanings of the formulation. For instance, although the terms \((R_m i_d)\) and \((R_m i_q)\) in (26) are the voltage drops due to the equivalent iron loss resistance \( R_m \), they are physically elements of speed emfs \((\omega_e \Psi_d), (\omega_e \Psi_q)\).

### V. RELATIONSHIP OF ELECTROMAGNETIC TORQUE FOR PARALLEL AND SERIES MODELS

#### A. Torque Equation for Parallel Model

The electromagnetic torque \( \tau \) for the parallel model is derived from the interaction between the \( d \rightarrow q \) axes line currents \( (i_d, i_q) \) and flux linkages \( (\Psi_d, \Psi_q) \) as

\[
\tau = P(\Psi_{d i_d} - \Psi_{q i_d}) = P(\Psi_{d i_{qm}} - \Psi_{q i_{dm}}) + P(\Psi_{d i_q} - \Psi_{q i_d})
\]

\[
= PK_e i_{qm} + \frac{1}{\omega_e} \left( \frac{L_m^2}{R} \Psi_d \Psi_q + \frac{1}{\omega_e} \right)
\] (27)

where the first term in the right-hand side corresponds to the output torque and the second term corresponds to the loss torque due to the iron loss. It is noted that multiplying the second term in (27) by the mechanical angular velocity \( \omega_m \) gives the iron loss \( P_i \) defined in (4).

#### B. Torque Equation for Series Model

The electromagnetic torque \( \tau \) for the series model is derived from the interaction between the \( d \rightarrow q \) axes line currents and flux linkages, which is calculated from (7) to (9) together with the relations \( R_m \simeq (\omega_e L)^2 / R_3 \), \( L_m \simeq L \), and \( K_{em} \simeq K_e \), as

\[
\tau = P(\Psi_{d i_d} - \Psi_{q i_d})
\]

\[
= PK_e \left\{ i_q - \frac{R_m}{\omega_e L} \left( i_d + \frac{K_e}{L} \right) \right\}
\]

\[
+ P \frac{R_m}{\omega_e} \left\{ \left( i_d + \frac{K_e}{L} \right)^2 + i_q^2 \right\}.
\] (28)
From (19), the first term in the right-hand side in (28) is identical to the output torque for the parallel model as follows:

First term
\[ PK_e \left\{ i_q - \frac{\omega_L}{R_e} \left( i_d + \frac{K_e}{L} \right) \right\} \]
\[ = PK_e i_{q_m}. \]  (29)

Multiplying the second term in the right-hand side in (28) by the mechanical angular velocity \( \omega_m \) gives

Second term \( \times \omega_m \)
\[ \omega_m P_m \frac{P_m}{\omega_e} \left\{ \frac{i_d + K_e}{L} \right\}^2 + i_q^2 \]
\[ = R_m \left\{ \left( i_d + \frac{K_e}{L} \right)^2 + i_q^2 \right\}. \]  (30)

It is noted that (30) is identical to the iron loss \( P_i \). Actually, substituting (24) into (6) and replacing the term \( (\omega_e^2 L^2 / R_3) \) with \( P_m \) yields (30).

It follows from above mathematical developments that although the torque equations for two types of model differ on appearances, they are mathematically the same.

VI. SUMMARY OF RELATIONSHIP BETWEEN PARALLEL AND SERIES MODELS

The relationship of the parallel and series models for PMSM is summarized as follows.

1) Although the flux linkage equations and voltage equations for two types of model differ on appearances, they are mathematically the same. The mathematical equivalence of them can be interpreted as the equivalent transformation between parallel and series electrical circuits. In addition, the torque equations for two types of model are mathematically the same although they also differ on appearances.

2) In the parallel model, the iron loss \( P_i \) arises from the iron loss resistance \( R_e \). Since the iron loss resistance is inserted in the armature circuit, the iron loss can be obtained directly from the \( d-q \) axes equivalent circuit of PMSM shown in Fig. 1. In the series model, the iron loss \( P_i \) arises from the resistance \( R_3 \) of the eddy current circuit. Since the armature circuit includes only added emfs by the magnetic coupling of the eddy current circuit, the iron loss cannot be obtained directly from the equivalent circuit of PMSM shown in Fig. 2. Alternatively, the iron loss is obtained directly from the eddy current circuit indicated in (6). Fortunately, as indicated in (30), the iron loss can also be calculated by using the quantities of the armature circuit.

3) The parallel model is superior in understanding the physical meaning to the series model. The parallel model is capable of expressing physical phenomena evidently, while the series model cannot be understood intuitively. By contrast, the series model is superior in low order of the state variables to the parallel model. The number of states variables increases due to the magnetizing currents. In addition, the magnetizing currents should be estimated because they cannot be obtained directly.

VII. CONCLUSION

This paper has investigated the relationship for the parallel and series models for PMSM taking iron loss into account. The expressions of the flux linkage for two types of model are mathematically developed and compared. The investigation has revealed the mathematical equivalence of the parallel and series models. In addition, the properties of the models are exhibited. The parallel model is superior in understanding the physical meaning to the series model. The series model is superior in low order of the state variables to the parallel model.

APPENDIX

Fig. A1 shows the \( d-q \) axes equivalent circuits of PMSM taking iron loss into account. The \( d \)-axis equivalent circuit consists of the armature circuit, field circuit, and added eddy current circuit. The \( q \)-axis equivalent circuit consists of the armature circuit and the eddy current circuit. The iron loss arises from the resistance \( R_3 \) of the eddy current circuit.

From Fig. A1, the \( d-q \) axes flux linkages for the armature circuit are given as

\[ \Psi_d = L_d i_d + M_{3d} i_3q + M_{12d} i_{12} \]
\[ \Psi_q = L_q i_q + M_{3q} i_3 + M_{12q} i_{12} \]  (A.1)

The eddy current circuit is short circuit and its voltage equations is expressed as

\[ 0 = R_3 i_3 + p \Psi_3 - \omega_L \Psi_3 \]
\[ 0 = R_3 i_3 + p \Psi_3 + \omega_L \Psi_3 \]  (A.2)

where the flux linkages are given as

\[ \Psi_3 = L_3 i_3 + M_{3d} i_3 + M_{3q} i_3 \]
\[ \Psi_3 = L_3 i_3 + M_{12d} i_{12} + M_{12q} i_{12} \]  (A.3)

In steady-state condition, the equivalent eddy currents are derived from (A.2) and (A.3) as

\[ i_d = \frac{\Psi_d}{L_d + \omega_L M_{12d}} i_d + \frac{R_3 L_3 i_3 - \omega_L M_{12d} i_{12}}{L_d + \omega_L M_{12d}} \]
\[ i_q = \frac{\Psi_q}{L_q + \omega_L M_{12q}} i_q - \frac{R_3 L_3 i_3 - \omega_L M_{12q} i_{12}}{L_q + \omega_L M_{12q}} \]  (A.4)

Substituting (A.4) into (A.1) results in the flux linkages expressed in the form of

\[ \Psi_d = \left( L_1 - \frac{\omega_L M_{12d}}{R_3 + \omega_L M_{12d}} \right) i_d + \frac{R_3 M_{3d} i_3 - \omega_L M_{12d} i_{12}}{R_3 + \omega_L M_{12d}} \]
\[ \Psi_q = \left( L_1 - \frac{\omega_L M_{12q}}{R_3 + \omega_L M_{12q}} \right) i_q - \frac{R_3 M_{3q} i_3 - \omega_L M_{12q} i_{12}}{R_3 + \omega_L M_{12q}} \]  (A.5)

Neglecting leakage inductances in both the armature and eddy current circuits gives the following relations:

\[ L_1 \simeq L_3 \simeq M_{33} = L \]
\[ M_{12} \simeq M_{32} \]  (A.6)
Fig. A1. $d-q$ axes equivalent circuits of PMSM taking iron loss into account. (a) $d$-axis. (b) $q$-axis.

It is noted that (A.3) is equal to (A.1) when the relations are true. Applying the relations to (A.5) results in the flux linkages as

$$
\psi_d = \frac{R_3^2}{R_3^2 + \omega_e^2 L_2^2} L_i d + \frac{\omega_e L_2}{R_3^2 + \omega_e^2 L_2^2} R_3 i q + \frac{R_3^2}{R_3^2 + \omega_e^2 L_2^2} K_e$$

$$
\psi_q = \frac{R_3^2}{R_3^2 + \omega_e^2 L_2^2} L_i q - \frac{\omega_e L_2}{R_3^2 + \omega_e^2 L_2^2} R_3 i d - \frac{\omega_e L}{R_3^2 + \omega_e^2 L_2^2} R_3 K_e
$$

(A.7)

where $K_e = M_2^d i_d$ corresponds to the permanent magnet flux. Defining the equivalent iron loss resistance $R_{m}$, equivalent armature inductance $L_m$, and equivalent emf constant $K_{em}$ as (10) to (12), respectively, it is seen that (A.7) becomes (7).

REFERENCES


Naomitsu Urasaki (M’98) was born in Okinawa Prefecture, Japan, in 1973. He received the B.S. and M.S. degrees in electrical engineering from the University of the Ryukyus, Okinawa, Japan, in 1996 and 1998, respectively. Currently, he is a Research Associate with the Department of Electrical and Electronics Engineering, Faculty of Engineering at the University of the Ryukyu, where he has been since 1998. His research interests are in the areas of modeling and control of ac motors. Mr. Urasaki is a member of the Institute of Electrical Engineers of Japan.

Tomonobu Senjyu (M’02) was born in Saga Prefecture, Japan, in 1963. He received the B.S. and M.S. degrees in electrical engineering from the University of the Ryukyu, Okinawa, Japan, in 1986 and 1988, respectively, and the Ph.D. degree in electrical engineering from Nagoya University, Nagoya, Japan, in 1994. Currently, he is a Professor with the Department of Electrical and Electronics Engineering, Faculty of Engineering at the University of the Ryukyu, where he has been since 1988. His research interests are in the areas of stability of ac machines, advanced control of electrical machines, and power electronics. Dr. Senjyu is a member of the Institute of Electrical Engineers of Japan.

Katsunori Uezato was born in Okinawa Prefecture, Japan, in 1940. He received the B.S. degree in electrical engineering from the University of the Ryukyu, Okinawa, Japan, in 1963, the M.S. degree in electrical engineering from Kagoshima University, Kagoshima, Japan, in 1972, and the Ph.D. degree in electrical engineering from Nagoya University, Nagoya, Japan, in 1983. Currently, he is a Professor with the Department of Electrical and Electronics Engineering, Faculty of Engineering at the University of the Ryukyu, where he has been since 1972. He is engaged in research on stability and control of synchronous machines. Dr. Uezato is a member of the Institute of Electrical Engineers of Japan.