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同期座標軸上電流制御ループを用いた速度センサレスベクトル制御系の線形化モデル

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A Linearized Model for Vector Control of Induction Motor without Speed Sensor Taking into Account the Effects of Current Control Loop in the Synchronously Rotating Reference Frame

Kazuhiro OYAMA and Katsuji SHINOHARA

The characteristics of a current control loop have great implications for stability of vector control of induction motor without speed sensor. The current control loop is composed in the synchronously rotating reference frame or in the three phase stationary reference frame.

In this paper, we derived the linearized model for vector control of induction motor without speed sensor taking into account the effects of current control loop in the synchronously rotating reference frame by using standard small signal analysis techniques. Next, the transfer function between the rotor speed ω_r and the rotor speed command ω_r^* are computed to study the influences of the current control loop on the stability.

1. まえがき

筆者らは先にトルク成分電流と二次磁束の演算値をフィードバックする速度センサレスベクトル制御系において、三相静止軸上で PI 制御を行っている電流制御ループを考慮した安定性解析を報告した⁽¹⁾。その中で電流制御器の比例ゲインを小さくしていくと速度センサレスベクトル制御系の方が速度センサ付きベクトル制御系よりも早く不安定になることを示した。両者の違いの原因として、電流制御誤差が一次電流を用いたトルク成分電流と二次磁束の演算に影響を与えることが考えられる。従って、定常状態において必ず一次電流指令と実際の一次電流が一致する dq 同期軸上での電流制御ループを用いることにより安定性が改善されることが予想される。

本稿では、先に検討した三相静止軸での電流制御ループを用いた速度センサレスベクトル制御系と比較を行うために、 dq 同期軸上で構成された電流制御ル

ープを用いた速度センサレスベクトル制御系を記述する非線形連立微分方程式とその線形化微分方程式を導出した。また、数式の共通部分を同じ記号で置き換えると三相静止軸上での電流制御ループを用いた場合においても線形化微分方程式が簡単化されたので付録 2 において合わせて報告する。

2. 線形化モデルの導出

2.1 解析モデル

図 1 に dq 同期軸上電流制御ループを用いた速度センサレスベクトル制御系を示す。 dq 同期軸上電流制御ループでは検出してきた一次電流を三相- dq 変換することにより得られる磁束成分電流 i_{1d} とトルク成分電流 i_{1q} をそれぞれ指令値 i_{1d}^* と i_{1q}^* に対して PI 制御を行う構成である。その他の構成は、先に報告した三相静止軸上電流制御ループを用いた場合⁽¹⁾と共通である。

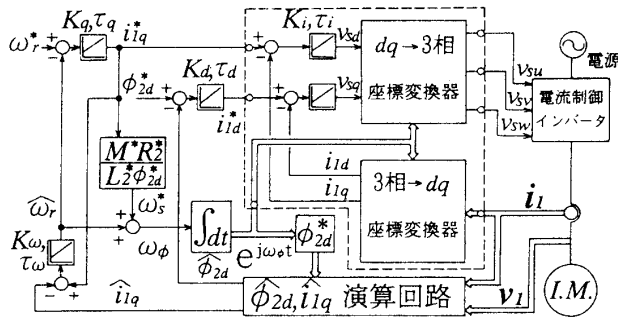


図1 dq同期軸上電流制御ループを用いた速度センサレスベクトル制御系

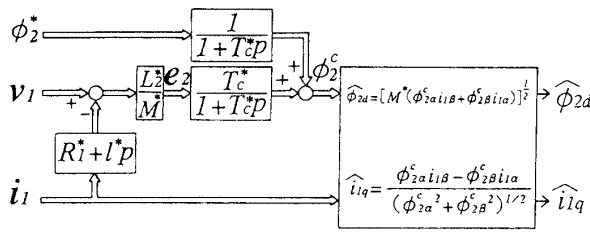


図2 $\hat{\phi}_{2d}$, \hat{i}_{1q} 演算回路

2. 2 連立微分方程式の導出

2.1で述べた通り電流制御ループの構成以外は文献[1]と同じであるので、ここではdq同期軸上での電流制御ループの式の導出のみを行い、その他の式の導出は文献[1]に譲る。

図1の破線で囲まれているdq同期軸上電流制御ループのPI制御部は次式で表せる。

$$v_{sd} = K_i \left(1 + \frac{1}{\tau_i p} \right) (i_{1d}^* - i_{1d}) \dots\dots\dots (1)$$

$$v_{sq} = K_i \left(1 + \frac{1}{\tau_i p} \right) (i_{1q}^* - i_{1q}) \dots\dots\dots (2)$$

(1)(2)式の両辺にpをかけ整理すると次式が得られる。

$$p v_{sd} = K_i (p i_{1d}^* - p i_{1d}) + \frac{K_i}{\tau_i} (i_{1d}^* - i_{1d}) \dots\dots\dots (3)$$

$$p v_{sq} = K_i (p i_{1q}^* - p i_{1q}) + \frac{K_i}{\tau_i} (i_{1q}^* - i_{1q}) \dots\dots\dots (4)$$

従って、文献[1]の式を引用すると誘導機の式(5)~(8)、機械系の式(9)、 $\hat{\phi}_{2d}$, \hat{i}_{1q} 演算回路の式(10)(11)、トルク制御器の式(12)、速度制御器の式(13)、磁束制御器の式(14)を含みdq同期軸上電流制御ループを用いた速度センサレスベクトル制御系は次式で記述される。

$$p i_{1d} = (1/\Delta) \{ -L_2 R_1 i_{1d} + (\omega_\phi L_1 L_2 - \omega_s M^2) i_{1q} + R_2 M i_{2d} + (\omega_\phi L_2 M - \omega_s L_2 M) i_{2q} + L_2 v_{1d} \} \dots\dots\dots (5)$$

$$p i_{1q} = (1/\Delta) \{ (-\omega_\phi L_1 L_2 + \omega_s M^2) i_{1d} - R_1 L_2 i_{1q} + (-\omega_\phi L_2 M + \omega_s L_2 M) i_{2d} + R_2 M i_{2q} + L_2 v_{1q} \} \dots\dots\dots (6)$$

$$p i_{2d} = (1/\Delta) \{ R_1 M i_{1d} + (-\omega_\phi L_1 M + \omega_s L_1 M) i_{1q} - R_2 L_1 i_{2d} + (-\omega_\phi M^2 + \omega_s L_1 L_2) i_{2q} - M v_{1d} \} \dots\dots\dots (7)$$

$$p i_{2q} = (1/\Delta) \{ (\omega_\phi L_1 M - \omega_s L_1 M) i_{1d} + R_1 M i_{1q} + (\omega_\phi M^2 - \omega_s L_1 L_2) i_{2d} - R_2 L_1 i_{2q} - M v_{1q} \} \dots\dots\dots (8)$$

$$p \omega_r = (1/J) \{ (P/2) M (i_{1q} i_{2d} - i_{1d} i_{2q}) - T_L \} \dots\dots\dots (9)$$

$$p \phi_{2d}^c = (1/T_c^*) \{ \phi_{2d}^* + T_c^* L_2^*/M^* (v_{1d} - R_1^* i_{1d} - l^* p i_{1d} + \omega_\phi l^* i_{1q}) + T_c^* \omega_\phi \phi_{2q}^c - \phi_{2d}^c \} \dots\dots\dots (10)$$

$$p \phi_{2q}^c = (1/T_c^*) \{ T_c^* L_2^*/M^* (v_{1q} - R_1^* i_{1q} - l^* p i_{1q} - \omega_\phi l^* i_{1d}) - T_c^* \omega_\phi \phi_{2d}^c - \phi_{2q}^c \} \dots\dots\dots (11)$$

$$p \hat{\omega}_r = \{ 1/(1+K_\omega K_q) \} \{ -K_\omega p \hat{i}_{1q} + (K_\omega/\tau_\omega) (i_{1q}^* - \hat{i}_{1q}) + K_\omega K_q (P/2) p \omega_r^* + (K_\omega K_q/\tau_q) \{ (P/2) \omega_r^* - \hat{\omega}_r \} \} \dots\dots\dots (12)$$

$$p i_{1q}^* = \{ 1/(1+K_\omega K_q) \} \{ K_\omega K_q p \hat{i}_{1q} - (K_\omega K_q/\tau_\omega) \times (i_{1q}^* - \hat{i}_{1q}) + K_q (P/2) p \omega_r^* + (K_q/\tau_q) \{ (P/2) \omega_r^* - \hat{\omega}_r \} \} \dots\dots\dots (13)$$

$$p i_{1d}^* = K_d (p \phi_{2d}^* + \phi_{2d}^*/\tau_d - p \hat{\phi}_{2d} - \hat{\phi}_{2d}/\tau_d) \dots\dots\dots (14)$$

$$p v_{sd} = K_i (p i_{1d}^* - p i_{1d}) + K_i/\tau_i (i_{1d}^* - i_{1d}) \dots\dots\dots (15)$$

$$p v_{sq} = K_i (p i_{1q}^* - p i_{1q}) + K_i/\tau_i (i_{1q}^* - i_{1q}) \dots\dots\dots (16)$$

ただし、
 $l = L_1 - \frac{M^2}{L_2}$, $l^* = L_1^* - \frac{M^{*2}}{L_2^*}$
 $\Delta = L_1 L_2 - M^2 = L_2 l \dots\dots\dots (17)$

$$\omega_\phi = \hat{\omega}_r + \frac{M^* R_2^*}{L_2^* \phi_{2d}^*} i_{1q}^*, \quad \omega_s = \omega_\phi - \frac{P}{2} \omega_r \dots\dots\dots (18)$$

$$\begin{cases} v_{1d} = K_v v_{sd} \dots\dots\dots (19) \\ v_{1q} = K_v v_{sq} \end{cases}$$

$$\hat{\phi}_{2d} = \sqrt{M^* (\phi_{2d}^c i_{1d} + \phi_{2q}^c i_{1q})} \dots\dots\dots (20)$$

$$\hat{i}_{1q} = \frac{\phi_{2d}^c i_{1q} - \phi_{2q}^c i_{1d}}{\sqrt{\phi_{2d}^{c2} + \phi_{2q}^{c2}}} \dots\dots\dots (21)$$

2. 3 線形化微分方程式の導出

2. 3. 1 線形化の準備

ω_ϕ の式において動作点近傍の微小変動を考えると、

$$\omega_\phi + \Delta\omega_\phi = \widehat{\omega}_{r0} + \Delta\widehat{\omega}_r + \frac{M^* R_2^*}{L_2^* \phi_{2d}^*} (i_{1q0}^* + \Delta i_{1q}^*)$$

となる。 $g_1 = \frac{M^* R_2^*}{L_2^* \phi_{2d}^*}$ の置き換えをし、微小変化分と定常項を取り出すと次式が得られる。

$$\Delta\omega_\phi = \Delta\widehat{\omega}_r + g_1 \Delta i_{1q}^* \dots (22)$$

$$\omega_{\phi 0} = \widehat{\omega}_{r0} + g_1 i_{1q0}^* \dots (23)$$

二次磁束と電流の関係式は定常値を用い次式で表わせる。

$$\begin{cases} \phi_{2d0} = M i_{1d0} + L_2 i_{2d0} \\ \phi_{2q0} = M i_{1q0} + L_2 i_{2q0} \end{cases} \dots (24)$$

2. 3. 2 誘導機の式(5)~(8)の線形化

(5)式に(17)~(19)式を代入し整理する。

$$\begin{aligned} p i_{1d} = & -\frac{R_1}{l} i_{1d} + \left(\omega_\phi + \frac{PM^2}{2L_2 l} \omega_r \right) i_{1q} + \frac{R_2 M}{L_2 l} i_{2d} \\ & + \frac{PM}{2l} \omega_r i_{2q} + \frac{K_v}{l} v_{sd} \end{aligned}$$

動作点近傍での微小変動を与える。

$$\begin{aligned} (p i_{1d})_0 + p \Delta i_{1d} = & -\frac{R_1}{l} (i_{1d0} + \Delta i_{1d}) + \left\{ (\omega_{\phi 0} + \Delta\omega_\phi) \right. \\ & + \left. \frac{PM^2}{2L_2 l} (\omega_{r0} + \Delta\omega_r) \right\} (i_{1q0} + \Delta i_{1q}) \\ & + \frac{R_2 M}{L_2 l} (i_{2d0} + \Delta i_{2d}) + \frac{PM}{2l} (\omega_{r0} + \Delta\omega_r) \\ & \times (i_{2q0} + \Delta i_{2q}) + \frac{K_v}{l} (v_{sd0} + \Delta v_{sd}) \end{aligned}$$

微小変化分だけを取り出すと、

$$\begin{aligned} p \Delta i_{1d} = & -\frac{R_1}{l} \Delta i_{1d} + \omega_{\phi 0} \Delta i_{1q} + i_{1q0} \Delta\omega_\phi + \frac{PM^2}{2L_2 l} \omega_{r0} \Delta i_{1q} \\ & + \frac{PM^2}{2L_2 l} i_{1q0} \Delta\omega_r + \frac{R_2 M}{L_2 l} \Delta i_{2d} + \frac{PM}{2l} (\omega_{r0} \Delta i_{2q} \\ & + i_{2q0} \Delta\omega_r) + \frac{K_v}{l} \Delta v_{sd} \end{aligned}$$

となる。上式に(22)式を代入し(24)式の置き換えを行い整理すると次式が得られる。

$$\begin{aligned} p \Delta i_{1d} = & -\frac{R_1}{l} \Delta i_{1d} + \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) \Delta i_{1q} + \frac{R_2 M}{L_2 l} \Delta i_{2d} \\ & + \frac{PM}{2l} \omega_{r0} \Delta i_{2q} + \frac{PM \phi_{2q0}}{2L_2 l} \Delta\omega_r + i_{1q0} \Delta\widehat{\omega}_r \\ & + g_1 i_{1q0} \Delta i_{1q}^* + \frac{K_v}{l} \Delta v_{sd} \dots (25) \end{aligned}$$

以下(5)式の場合と同じ手順を踏み(6)~(8)式の微小変化分を計算すると次のようになる。(6)式より、

$$\begin{aligned} p \Delta i_{1q} = & -\left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) \Delta i_{1d} - \frac{R_1}{l} \Delta i_{1q} - \frac{PM}{2l} \omega_{r0} \Delta i_{2d} \\ & + \frac{R_2 M}{L_2 l} \Delta i_{2q} - \frac{PM \phi_{2d0}}{2L_2 l} \Delta\omega_r - i_{1d0} \Delta\widehat{\omega}_r - g_1 i_{1d0} \Delta i_{1q}^* \\ & + \frac{K_v}{l} \Delta v_{sq} \dots (26) \end{aligned}$$

(7)式より、

$$\begin{aligned} p \Delta i_{2d} = & \frac{R_1 M}{L_2 l} \Delta i_{1d} - \frac{PL_1 M}{2L_2 l} \omega_{r0} \Delta i_{1q} - \frac{R_2 L_1}{L_2 l} \Delta i_{2d} \\ & + \left(\omega_{\phi 0} - \frac{PL_1}{2l} \omega_{r0} \right) \Delta i_{2q} - \frac{PL_1 \phi_{2q0}}{2L_2 l} \Delta\omega_r + i_{2q0} \Delta\widehat{\omega}_r \\ & + g_1 i_{2q0} \Delta i_{1q}^* - \frac{MK_v}{L_2 l} \Delta v_{sd} \dots (27) \end{aligned}$$

(8)式より、

$$\begin{aligned} p \Delta i_{2q} = & \frac{PL_1 M}{2L_2 l} \omega_{r0} \Delta i_{1d} + \frac{R_1 M}{L_2 l} \Delta i_{1q} - \left(\omega_{\phi 0} - \frac{PL_1}{2l} \omega_{r0} \right) \Delta i_{2d} \\ & - \frac{R_2 L_1}{L_2 l} \Delta i_{2q} + \frac{PL_1 \phi_{2d0}}{2L_2 l} \Delta\omega_r - i_{2d0} \Delta\widehat{\omega}_r \\ & - g_1 i_{2d0} \Delta i_{1q}^* - \frac{MK_v}{L_2 l} \Delta v_{sq} \dots (28) \end{aligned}$$

が得られる。

2. 3. 3 機械系の式(9)の線形化

(9)式において動作点近傍での微小変動を考えると、

$$\begin{aligned} (p \omega_r)_0 + p \Delta\omega_r = & \frac{1}{J} \left[\left(\frac{P}{2} \right) M \{ (i_{1q0} + \Delta i_{1q}) (i_{2d0} + \Delta i_{2d}) \right. \\ & \left. - (i_{1d0} + \Delta i_{1d}) (i_{2q0} + \Delta i_{2q}) \} - T_L \right] \end{aligned}$$

となる。微小変化分を取り出すと次式になる。

$$\begin{aligned} p \Delta\omega_r = & -\frac{PM}{2J} i_{2q0} \Delta i_{1d} + \frac{PM}{2J} i_{2d0} \Delta i_{1q} + \frac{PM}{2J} i_{1q0} \Delta i_{2d} \\ & - \frac{PM}{2J} i_{1d0} \Delta i_{2q} \dots (29) \end{aligned}$$

2. 3. 4 $\widehat{\phi}_{2d}$, \widehat{i}_{1q} 演算回路の式(10)(11)の線形化

(10)式において(19)式を代入し動作点近傍での微小変動を考えると、

$$\begin{aligned} (p \phi_{2d}^c)_0 + p \Delta \phi_{2d}^c = & \frac{1}{T_c^*} \left[\phi_{2d0}^* + T_c^* \frac{L_2^*}{M^*} [K_v (v_{sd0} + \Delta v_{sd}) \right. \\ & - R_1^* (i_{1d0} + \Delta i_{1d}) - l^* \{ (p i_{1d})_0 \\ & + p \Delta i_{1d} \} + (\omega_{\phi 0} + \Delta\omega_\phi) l^* (i_{1q0} + \Delta i_{1q}) \\ & + T_c^* (\omega_{\phi 0} + \Delta\omega_\phi) (\phi_{2q0}^c + \Delta \phi_{2q}^c) \\ & \left. - (\phi_{2d0}^c + \Delta \phi_{2d}^c) \right] \end{aligned}$$

となる。微小変化分だけを取り出すと次式になる。

$$p\Delta\phi_{2d}^c = \frac{1}{T_c^*} \left[T_c^* \frac{L_2^*}{M^*} \{K_v \Delta v_{sd} - R_1^* \Delta i_{1d} - l^* p \Delta i_{1d} + l^* \omega_{\phi 0} \Delta i_{1q} + l^* i_{1q0} \Delta \omega_{\phi}\} + T_c^* \omega_{\phi 0} \Delta \phi_{2q}^c + T_c^* \phi_{2q0}^c \Delta \omega_{\phi} - \Delta \phi_{2d}^c \right]$$

上式に(22), (25)式を代入して整理すると次式が得られる。

$$p\Delta\phi_{2d}^c = \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \Delta i_{1d} - \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \Delta i_{1q} - \frac{L_2^*}{M^*} \frac{l^* R_2 M}{L_2 l} \Delta i_{2d} - \frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0} \Delta i_{2q} - \frac{L_2^*}{M^*} \frac{l^* PM \phi_{2q0}}{2L_2 l} \Delta \omega_r - \frac{1}{T_c^*} \Delta \phi_{2d}^c + \omega_{\phi 0} \Delta \phi_{2q}^c + \phi_{2q0}^c \Delta \widehat{\omega}_r + g_1 \phi_{2q0}^c \Delta i_{1q}^* + \frac{L_2^*}{M^*} \left(1 - \frac{l^*}{l} \right) K_v \Delta v_{sd} \dots \dots \dots (30)$$

(11)式においても(10)式と同じ手順を踏み微小変化分を計算すると次式が得られる。

$$p\Delta\phi_{2q}^c = \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \Delta i_{1d} + \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \Delta i_{1q} + \frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0} \Delta i_{2d} - \frac{L_2^*}{M^*} \frac{l^* R_2 M}{L_2 l} \Delta i_{2q} + \frac{L_2^*}{M^*} \frac{l^* PM \phi_{2d0}}{2L_2 l} \Delta \omega_r - \omega_{\phi 0} \Delta \phi_{2d}^c - \frac{1}{T_c^*} \Delta \phi_{2q}^c - \phi_{2d0}^c \Delta \widehat{\omega}_r - g_1 \phi_{2d0}^c \Delta i_{1q}^* + \frac{L_2^*}{M^*} \left(1 - \frac{l^*}{l} \right) K_v \Delta v_{sq} \dots \dots \dots (31)$$

2. 3. 5 トルク制御器の式(12)の線形化

まず(12)式の中に含まれる \widehat{i}_{1q} と $p\widehat{i}_{1q}$ の線形化を行う。(21)式において動作点近傍での微小変動を考える。

$$\widehat{i}_{1q0} + \Delta \widehat{i}_{1q} = \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c) (i_{1q0} + \Delta i_{1q}) - (\phi_{2q0}^c + \Delta \phi_{2q}^c) (i_{1d0} + \Delta i_{1d}) \} \times \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c)^2 + (\phi_{2q0}^c + \Delta \phi_{2q}^c)^2 \}^{-\frac{1}{2}}$$

微小変化分の積を零とすると次のようになる。

$$\widehat{i}_{1q0} + \Delta \widehat{i}_{1q} = (\phi_{2d0}^c i_{1q0} + \phi_{2d0}^c \Delta i_{1q} + i_{1q0} \Delta \phi_{2d}^c - \phi_{2q0}^c i_{1d0} - \phi_{2q0}^c \Delta i_{1d} - i_{1d0} \Delta \phi_{2q}^c) \times \{ (\phi_{2d0}^c + \phi_{2q0}^c)^2 + 2\phi_{2d0}^c \Delta \phi_{2d}^c + 2\phi_{2q0}^c \Delta \phi_{2q}^c \}^{-\frac{1}{2}}$$

上式の $()^{-\frac{1}{2}}$ 項において $(1 + \Delta x)^n \cong 1 + n\Delta x$ の近似を行うと次のようになる。

$$\widehat{i}_{1q0} + \Delta \widehat{i}_{1q} = (\phi_{2d0}^c i_{1q0} - \phi_{2q0}^c i_{1d0} - \phi_{2q0}^c \Delta i_{1d} + \phi_{2d0}^c \Delta i_{1q} + i_{1q0} \Delta \phi_{2d}^c - i_{1d0} \Delta \phi_{2q}^c) \times \{ (\phi_{2d0}^c + \phi_{2q0}^c)^2 \}^{-\frac{1}{2}} \times \{ 1 - (\phi_{2d0}^c + \phi_{2q0}^c)^{-1} (\phi_{2d0}^c \Delta \phi_{2d}^c + \phi_{2q0}^c \Delta \phi_{2q}^c) \}$$

上式を展開し微小変化分だけを取り出すと次式になる。

$$\Delta \widehat{i}_{1q} = - \{ (\phi_{2d0}^c + \phi_{2q0}^c)^{-\frac{1}{2}} \phi_{2q0}^c \Delta i_{1d} + (\phi_{2d0}^c + \phi_{2q0}^c)^{-\frac{1}{2}} \times \phi_{2d0}^c \Delta i_{1q} + \{ (\phi_{2d0}^c + \phi_{2q0}^c)^{-\frac{1}{2}} i_{1q0} - (\phi_{2d0}^c + \phi_{2q0}^c)^{-\frac{3}{2}} \times (\phi_{2d0}^c i_{1q0} - \phi_{2q0}^c i_{1d0}) \phi_{2d0}^c \} \Delta \phi_{2d}^c + \{ - (\phi_{2d0}^c + \phi_{2q0}^c)^{-\frac{1}{2}} i_{1d0} - (\phi_{2d0}^c + \phi_{2q0}^c)^{-\frac{3}{2}} \times (\phi_{2d0}^c i_{1q0} - \phi_{2q0}^c i_{1d0}) \phi_{2q0}^c \} \Delta \phi_{2q}^c$$

ここで、 $|\phi_{20}^c| = (\phi_{2d0}^c + \phi_{2q0}^c)^{\frac{1}{2}}$, $g_{02} = \phi_{2q0}^c i_{1d0} - \phi_{2d0}^c i_{1q0}$ とおくと次式が得られる。

$$\Delta \widehat{i}_{1q} = - \frac{1}{|\phi_{20}^c|} \phi_{2q0}^c \Delta i_{1d} + \frac{1}{|\phi_{20}^c|} \phi_{2d0}^c \Delta i_{1q} + \left\{ \frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right\} \Delta \phi_{2d}^c + \left\{ - \frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right\} \Delta \phi_{2q}^c \dots \dots \dots (32)$$

(21)式を時間微分すると次式が得られる。

$$p\widehat{i}_{1q} = (i_{1q} p\phi_{2d}^c + \phi_{2d}^c p i_{1q} - i_{1d} p\phi_{2q}^c - \phi_{2q}^c p i_{1d}) \times \{ (\phi_{2d}^c + \phi_{2q}^c)^2 \}^{-\frac{1}{2}} - (\phi_{2d}^c i_{1q} - \phi_{2q}^c i_{1d}) \times \{ (\phi_{2d}^c p\phi_{2d}^c + \phi_{2q}^c p\phi_{2q}^c) (\phi_{2d}^c + \phi_{2q}^c)^{-\frac{3}{2}}$$

上式において動作点近傍の微小変動を与えると次式のようなになる。

$$(p\widehat{i}_{1q})_0 + p\Delta \widehat{i}_{1q} = \{ (i_{1q0} + \Delta i_{1q}) p(\phi_{2d0}^c + \Delta \phi_{2d}^c) + (\phi_{2d0}^c + \Delta \phi_{2d}^c) \times p(i_{1q0} + \Delta i_{1q}) - (i_{1d0} + \Delta i_{1d}) p(\phi_{2q0}^c + \Delta \phi_{2q}^c) - (\phi_{2q0}^c + \Delta \phi_{2q}^c) p(i_{1d0} + \Delta i_{1d}) \} \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c)^2 + (\phi_{2q0}^c + \Delta \phi_{2q}^c)^2 \}^{-\frac{1}{2}} - \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c) (i_{1q0} + \Delta i_{1q}) - (\phi_{2q0}^c + \Delta \phi_{2q}^c) (i_{1d0} + \Delta i_{1d}) \} \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c) \times p(\phi_{2d0}^c + \Delta \phi_{2d}^c) + (\phi_{2q0}^c + \Delta \phi_{2q}^c) p(\phi_{2d0}^c + \Delta \phi_{2d}^c) \} \times \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c)^2 + (\phi_{2q0}^c + \Delta \phi_{2q}^c)^2 \}^{-\frac{3}{2}}$$

微小変化分どうしの積を零にしながらか展開すると次式のようなになる。

$$(p\widehat{i}_{1q})_0 + p\Delta \widehat{i}_{1q} = (\text{前半}) + (\text{後半})$$

ここで、

$$\begin{aligned} \text{(前半)} = & \{i_{1q0} p \Delta \phi_{2d}^c + \phi_{2d0}^c p \Delta i_{1q} - i_{1d0} p \Delta \phi_{2q}^c - \phi_{2q0}^c p \Delta i_{1d}\} \\ & \times (\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2} + 2\phi_{2d0}^c \Delta \phi_{2d}^c + 2\phi_{2q0}^c \Delta \phi_{2q}^c)^{-\frac{1}{2}} \\ & \dots\dots\dots (33) \end{aligned}$$

$$\begin{aligned} \text{(後半)} = & \{\phi_{2d0}^c i_{1q0} p \Delta \phi_{2d}^c + \phi_{2d0}^c \phi_{2q0}^c i_{1q0} p \Delta \phi_{2q}^c \\ & - \phi_{2d0}^c \phi_{2q0}^c i_{1d0} p \Delta \phi_{2d}^c - \phi_{2q0}^c i_{1d0} p \Delta \phi_{2q}^c\} \\ & \times (\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2} + 2\phi_{2d0}^c \Delta \phi_{2d}^c + 2\phi_{2q0}^c \Delta \phi_{2q}^c)^{-\frac{3}{2}} \\ & \dots\dots\dots (34) \end{aligned}$$

(33)式に(25)(26)(30)(31)式を代入し、 $()^{-\frac{3}{2}}$ 項において $(1+\Delta x)^n \approx 1+n\Delta x$ の近似を用いると次のようになる。ただし、 a_{nm} は付録1で示してあるAのn行m列の成分である。

$$\begin{aligned} \text{(前半)} = & \{-\phi_{2q0}^c (a_{11} \Delta i_{1d} + a_{12} \Delta i_{1q} + a_{13} \Delta i_{2d} + a_{14} \Delta i_{2q} \\ & + a_{15} \Delta \omega_r + a_{18} \widehat{\Delta \omega_r} + a_{19} \Delta i_{1q}^* + a_{1,11} \Delta v_{sd}) \\ & + \phi_{2d0}^c (a_{21} \Delta i_{1d} + a_{22} \Delta i_{1q} + a_{23} \Delta i_{2d} + a_{24} \Delta i_{2q} \\ & + a_{25} \Delta \omega_r + a_{28} \widehat{\Delta \omega_r} + a_{29} \Delta i_{1q}^* + a_{2,12} \Delta v_{sq}) \\ & + i_{1q0} (a_{61} \Delta i_{1d} + a_{62} \Delta i_{1q} + a_{63} \Delta i_{2d} + a_{64} \Delta i_{2q} \\ & + a_{65} \Delta \omega_r + a_{66} \Delta \phi_{2d}^c + a_{67} \Delta \phi_{2q}^c + a_{68} \widehat{\Delta \omega_r} \\ & + a_{69} \Delta i_{1q}^* + a_{6,11} \Delta v_{sd}) - i_{1d0} (a_{71} \Delta i_{1d} \\ & + a_{72} \Delta i_{1q} + a_{73} \Delta i_{2d} + a_{74} \Delta i_{2q} + a_{75} \Delta \omega_r \\ & + a_{76} \Delta \phi_{2d}^c + a_{77} \phi_{2q}^c + a_{78} \widehat{\Delta \omega_r} + a_{79} \Delta i_{1q}^* \\ & + a_{7,12} \Delta v_{sq})\} (\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2})^{-\frac{1}{2}} \{1 - (\phi_{2d0}^{c^2} \\ & + \phi_{2q0}^{c^2})^{-1} (\phi_{2d0}^c \Delta \phi_{2d}^c + \phi_{2q0}^c \Delta \phi_{2q}^c) \dots\dots\dots (35) \end{aligned}$$

(35)式の微小変化分だけを取り出すと次式が得られる。

(前半の微小変化分)

$$\begin{aligned} = & g_3 \Delta i_{1d} + g_4 \Delta i_{1q} + g_5 \Delta i_{2d} + g_6 \Delta i_{2q} + g_7 \Delta \omega_r + g_8 \Delta \phi_{2d}^c \\ & + g_9 \Delta \phi_{2q}^c + g_{10} \Delta v_{sd} + g_{11} \Delta v_{sq} \dots\dots\dots (36) \end{aligned}$$

上式の係数 $g_3 \sim g_{11}$ は、 $|\phi_{20}^c| = (\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2})^{\frac{1}{2}}$ とおき、次で表せる。

$$\begin{aligned} g_3 = & \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \left(-\frac{R_1}{l} \right) - \phi_{2d0}^c \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) \right. \\ & \left. + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) - i_{1d0} \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \right\} \\ g_4 = & \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) + \phi_{2d0}^c \left(-\frac{R_1}{l} \right) \right. \\ & \left. + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM^2}{2L_2 l} \omega_{r0} \right) - i_{1d0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \right\} \end{aligned}$$

$$\begin{aligned} g_5 = & \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{R_2 M}{L_2 l} + \phi_{2d0}^c \left(-\frac{PM}{2l} \omega_{r0} \right) \right. \\ & \left. + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) - i_{1d0} \frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0} \right\} \end{aligned}$$

$$\begin{aligned} g_6 = & \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{PM}{2l} \omega_{r0} + \phi_{2d0}^c \left(\frac{R_2 M}{L_2 l} \right) \right. \\ & \left. + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM}{2l} \omega_{r0} \right) - i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) \right\} \end{aligned}$$

$$\begin{aligned} g_7 = & \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{PM \phi_{2q0}}{2L_2 l} + \phi_{2d0}^c \left(-\frac{PM \phi_{2d0}}{2L_2 l} \right) \right. \\ & \left. + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM \phi_{2q0}}{2L_2 l} \right) - i_{1d0} \frac{L_2^*}{M^*} \frac{l^* PM \phi_{2d0}}{2L_2 l} \right\} \end{aligned}$$

$$g_8 = \frac{1}{|\phi_{20}^c|} \left\{ i_{1q0} \left(-\frac{1}{\Gamma_c^*} \right) - i_{1d0} (-\omega_{\phi 0}) \right\}$$

$$g_9 = \frac{1}{|\phi_{20}^c|} \left\{ i_{1q0} \omega_{\phi 0} - i_{1d0} \left(-\frac{1}{\Gamma_c^*} \right) \right\}$$

$$g_{10} = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{K_v}{l} + i_{1q0} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \right\}$$

$$g_{11} = \frac{1}{|\phi_{20}^c|} \left\{ \phi_{2d0}^c \frac{K_v}{l} - i_{1d0} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \right\}$$

(34)式に(30)(31)式を代入し、 $()^{-\frac{3}{2}}$ 項において $(1+\Delta x)^n \approx 1+n\Delta x$ の近似を用いると次のようになる。

$$\begin{aligned} \text{(後半)} = & \{(\phi_{2d0}^c \phi_{2q0}^c i_{1d0} - \phi_{2d0}^{c^2} i_{1q0}) (a_{61} \Delta i_{1d} + a_{62} \Delta i_{1q} \\ & + a_{63} \Delta i_{2d} + a_{64} \Delta i_{2q} + a_{65} \Delta \omega_r + a_{66} \Delta \phi_{2d}^c \\ & + a_{67} \Delta \phi_{2q}^c + a_{68} \widehat{\Delta \omega_r} + a_{69} \Delta i_{1q}^* + a_{6,11} \Delta v_{sd}) \\ & + (\phi_{2q0}^{c^2} i_{1d0} - \phi_{2d0}^c \phi_{2q0}^c i_{1q0}) (a_{71} \Delta i_{1d} + a_{72} \Delta i_{1q} \\ & + a_{73} \Delta i_{2d} + a_{74} \Delta i_{2q} + a_{75} \Delta \omega_r + a_{76} \Delta \phi_{2d}^c \\ & + a_{77} \Delta \phi_{2q}^c + a_{78} \widehat{\Delta \omega_r} + a_{79} \Delta i_{1q}^* + a_{7,12} \Delta v_{sq})\} \\ & \times (\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2})^{-\frac{3}{2}} \{1 - 3(\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2})^{-1} \\ & \times (\phi_{2d0}^c \Delta \phi_{2d}^c + \phi_{2q0}^c \Delta \phi_{2q}^c)\} \dots\dots\dots (37) \end{aligned}$$

(37)式の微小変化分だけを取り出すと次式が得られる。

(後半の微小変化分)

$$\begin{aligned} = & g_{12} \Delta i_{1d} + g_{13} \Delta i_{1q} + g_{14} \Delta i_{2d} + g_{15} \Delta i_{2q} + g_{16} \Delta \omega_r \\ & + g_{17} \Delta \phi_{2d}^c + g_{18} \Delta \phi_{2q}^c + g_{19} \Delta v_{sd} + g_{20} \Delta v_{sq} \dots\dots\dots (38) \end{aligned}$$

上式の係数 $g_{12} \sim g_{20}$ は、 $g_{02} = \phi_{2q0}^c i_{1d0} - \phi_{2d0}^c i_{1q0}$ 、

$|\phi_{20}^c| = (\phi_{2d0}^{c^2} + \phi_{2q0}^{c^2})^{\frac{1}{2}}$ とおくと次のようになる。

$$\begin{aligned}
 g_{12} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \right. \\
 &\quad \left. + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \frac{l^* P M^2}{2 L_2 l} \omega_{r0} \right\} \\
 g_{13} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* P M^2}{2 L_2 l} \omega_{r0} \right) \right. \\
 &\quad \left. + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \right\} \\
 g_{14} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) \right. \\
 &\quad \left. + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \frac{l^* P M}{2 l} \omega_{r0} \right\} \\
 g_{15} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* P M}{2 l} \omega_{r0} \right) \right. \\
 &\quad \left. + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) \right\} \\
 g_{16} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* P M \phi_{2q0}}{2 L_2 l} \right) \right. \\
 &\quad \left. + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \left(\frac{l^* P M \phi_{2d0}}{2 L_2 l} \right) \right\} \\
 g_{17} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \left(-\frac{1}{T_c^*} \right) + \phi_{2q0}^c g_{02} (-\omega_{\phi 0}) \right\} \\
 g_{18} &= \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \omega_{\phi 0} + \phi_{2q0}^c g_{02} \left(-\frac{1}{T_c^*} \right) \right\} \\
 g_{19} &= \frac{1}{|\phi_{20}^c|^3} \phi_{2d0}^c g_{02} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \\
 g_{20} &= \frac{1}{|\phi_{20}^c|^3} \phi_{2q0}^c g_{02} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v
 \end{aligned}$$

(36) (38) 式をまとめると $p\Delta\widehat{i}_{1q}$ になる。

$$\begin{aligned}
 p\Delta\widehat{i}_{1q} &= (g_3 + g_{12}) \Delta i_{1d} + (g_4 + g_{13}) \Delta i_{1q} + (g_5 + g_{14}) \Delta i_{2d} \\
 &\quad + (g_6 + g_{15}) \Delta i_{2q} + (g_7 + g_{16}) \Delta \omega_r + (g_8 + g_{17}) \Delta \phi_{2d}^c \\
 &\quad + (g_9 + g_{18}) \Delta \phi_{2q}^c + (g_{10} + g_{19}) \Delta v_{sd} \\
 &\quad + (g_{11} + g_{20}) \Delta v_{sq} \dots \dots \dots (39)
 \end{aligned}$$

(12) 式において、動作点近傍での微小変動を与えると、

$$\begin{aligned}
 (p\widehat{\omega}_r)_0 + p\Delta\widehat{\omega}_r &= \{1/(1 + K_\omega K_q)\} \{-K_\omega p(\widehat{i}_{1q0} + \Delta\widehat{i}_{1q}) + (K_\omega/\tau_\omega) \\
 &\quad \times \{(i_{1q0}^* + \Delta i_{1q}^*) - (\widehat{i}_{1q0} + \Delta\widehat{i}_{1q})\} \\
 &\quad + K_\omega K_q (P/2) p(\omega_{r0}^* + \Delta\omega_r^*) + (K_\omega K_q/\tau_q) \\
 &\quad \times \{(P/2)(\omega_{r0}^* + \Delta\omega_r^*) - (\widehat{\omega}_{r0} + \Delta\widehat{\omega}_r)\}
 \end{aligned}$$

となる。微小変化分だけを取り出すと次のようになる。

$$\begin{aligned}
 p\Delta\widehat{\omega}_r &= \{1/(1 + K_\omega K_q)\} \left(-K_\omega p\Delta\widehat{i}_{1q} + \frac{K_\omega}{\tau_\omega} \Delta i_{1q}^* - \frac{K_\omega}{\tau_\omega} \Delta\widehat{i}_{1q} \right. \\
 &\quad \left. + K_\omega K_q \frac{P}{2} p\Delta\omega_r^* + \frac{K_\omega K_q}{\tau_q} \frac{P}{2} \Delta\omega_r^* - \frac{K_\omega K_q}{\tau_q} \Delta\widehat{\omega}_r \right)
 \end{aligned}$$

上式に (32) (39) 式を代入し $g_2 = \frac{K_\omega}{1 + K_\omega K_q}$ とおくと次式が得られる。

$$\begin{aligned}
 p\Delta\widehat{\omega}_r &= -g_2 \left\{ (g_3 + g_{12}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \Delta i_{1d} \\
 &\quad - g_2 \left\{ (g_4 + g_{13}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \Delta i_{1q} \\
 &\quad - g_2 (g_5 + g_{14}) \Delta i_{2d} - g_2 (g_6 + g_{15}) \Delta i_{2q} \\
 &\quad - g_2 (g_7 + g_{16}) \Delta \omega_r - g_2 \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \right. \\
 &\quad \times \left. \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\} \Delta \phi_{2d}^c - g_2 \\
 &\quad \times \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\} \\
 &\quad \times \Delta \phi_{2q}^c - \frac{K_q}{\tau_q} g_2 \Delta\widehat{\omega}_r + \frac{1}{\tau_\omega} g_2 \Delta i_{1q}^* \\
 &\quad - g_2 (g_{10} + g_{19}) \Delta v_{sd} - g_2 (g_{11} + g_{20}) \Delta v_{sq} \\
 &\quad + \frac{K_\omega K_q}{1 + K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) \Delta\omega_r^* \dots \dots \dots (40)
 \end{aligned}$$

2. 3. 6 速度制御器の式(13)の線形化

(13) 式において、動作点近傍での微小変動を与えるとき、

$$\begin{aligned}
 (pi_{1q}^*)_0 + p\Delta i_{1q}^* &= \{1/(1 + K_\omega K_q)\} \{K_\omega K_q p(\widehat{i}_{1q0} + \Delta\widehat{i}_{1q}) \\
 &\quad - (K_\omega K_q/\tau_\omega) \{(i_{1q0}^* + \Delta i_{1q}^*) - (\widehat{i}_{1q0} + \Delta\widehat{i}_{1q})\} \\
 &\quad + K_q (P/2) p(\omega_{r0}^* + \Delta\omega_r^*) + (K_q/\tau_q) \\
 &\quad \times \{(P/2)(\omega_{r0}^* + \Delta\omega_r^*) - (\widehat{\omega}_{r0} + \Delta\widehat{\omega}_r)\}
 \end{aligned}$$

となる。微小変化分だけを取り出すと次のようになる。

$$\begin{aligned}
 p\Delta i_{1q}^* &= \{1/(1 + K_\omega K_q)\} \left(K_\omega K_q p\Delta\widehat{i}_{1q} - \frac{K_\omega K_q}{\tau_\omega} \Delta i_{1q}^* \right. \\
 &\quad \left. + \frac{K_\omega K_q}{\tau_\omega} \Delta\widehat{i}_{1q} + K_q \frac{P}{2} p\Delta\omega_r^* + \frac{K_q}{\tau_q} \frac{P}{2} \Delta\omega_r^* - \frac{K_q}{\tau_q} \Delta\widehat{\omega}_r \right)
 \end{aligned}$$

上式に (32) (39) 式を代入し $g_2 = \frac{K_\omega}{1 + K_\omega K_q}$ とおくと次式が得られる。

$$\begin{aligned}
 p\Delta i_{1q}^* &= K_q g_2 \left\{ (g_3 + g_{12}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \Delta i_{1d} + K_q g_2 \\
 &\times \left\{ (g_4 + g_{13}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \Delta i_{1q} + K_q g_2 \\
 &\times (g_5 + g_{14}) \Delta i_{2d} + K_q g_2 (g_6 + g_{15}) \Delta i_{2q} \\
 &+ K_q g_2 (g_7 + g_{16}) \Delta \omega_r + K_q g_2 \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \right. \\
 &\times \left. \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\} \Delta \phi_{2d}^c + K_q g_2 \\
 &\times \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\} \\
 &\times \Delta \phi_{2q}^c - \frac{K_q}{\tau_q K_\omega} g_2 \Delta \omega_r - \frac{K_q}{\tau_\omega} g_2 \Delta i_{1q}^* \\
 &+ K_q g_2 (g_{10} + g_{19}) \Delta v_{sd} + K_q g_2 (g_{11} + g_{20}) \Delta v_{sq} \\
 &+ \frac{K_q}{1 + K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) \Delta \omega_r^* \dots \dots \dots (41)
 \end{aligned}$$

2. 3. 7 磁束制御器の式(14)の線形化

まず、(14)式の中に含まれる $\widehat{\phi}_{2d}$ 、 $p\widehat{\phi}_{2d}$ の線形化を行う。(20)式において動作点近傍での微小変動を考える。

$$\begin{aligned}
 &\widehat{\phi}_{2d0} + \Delta \widehat{\phi}_{2d} \\
 &= \sqrt{M^*} \{ (\phi_{2d0}^c + \Delta \phi_{2d}^c) (i_{1d0} + \Delta i_{1d}) + (\phi_{2q0}^c + \Delta \phi_{2q}^c) (i_{1q0} + \Delta i_{1q}) \} \\
 &\text{微小変化分の積を零とし整理すると次式が得られる。} \\
 &\widehat{\phi}_{2d0} + \Delta \widehat{\phi}_{2d} \\
 &= \sqrt{M^*} (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{\frac{1}{2}} \\
 &\times \left(1 + \frac{\phi_{2d0}^c \Delta i_{1d} + \phi_{2q0}^c \Delta i_{1q} + i_{1d0} \Delta \phi_{2d}^c + i_{1q0} \Delta \phi_{2q}^c}{\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0}} \right)^{\frac{1}{2}}
 \end{aligned}$$

上式の ()^{1/2} 項において (1 + Δx)ⁿ ≃ 1 + nΔx の近似を行うと次のようになる。

$$\begin{aligned}
 &\widehat{\phi}_{2d0} + \Delta \widehat{\phi}_{2d} \\
 &= \sqrt{M^*} (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{\frac{1}{2}} \\
 &\times \left(1 + \frac{1}{2} \frac{\phi_{2d0}^c \Delta i_{1d} + \phi_{2q0}^c \Delta i_{1q} + i_{1d0} \Delta \phi_{2d}^c + i_{1q0} \Delta \phi_{2q}^c}{\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0}} \right)
 \end{aligned}$$

上式を展開し微小変化分だけを取り出すと次式になる。

$$\begin{aligned}
 \Delta \widehat{\phi}_{2d} &= \frac{\sqrt{M^*}}{2} (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{\frac{1}{2}} \phi_{2d0}^c \Delta i_{1d} \\
 &+ \frac{\sqrt{M^*}}{2} (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}} \phi_{2q0}^c \Delta i_{1q}
 \end{aligned}$$

$$\begin{aligned}
 &+ \frac{\sqrt{M^*}}{2} (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}} i_{1d0} \Delta \phi_{2d}^c \\
 &+ \frac{\sqrt{M^*}}{2} (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}} i_{1q0} \Delta \phi_{2q}^c
 \end{aligned}$$

ここで、 $g_{03} = \phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0}$ とおくと次式が得られる。

$$\begin{aligned}
 \Delta \widehat{\phi}_{2d} &= \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} \phi_{2d0}^c \Delta i_{1d} + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} \phi_{2q0}^c \Delta i_{1q} \\
 &+ \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} i_{1d0} \Delta \phi_{2d}^c + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} i_{1q0} \Delta \phi_{2q}^c \dots (42)
 \end{aligned}$$

(20)式を時間微分すると次式が得られる。

$$\begin{aligned}
 p\widehat{\phi}_{2d} &= \frac{\sqrt{M^*}}{2} (i_{1d} p\phi_{2d}^c + \phi_{2d}^c p i_{1d} + i_{1q} p\phi_{2q}^c \\
 &+ \phi_{2q}^c p i_{1q}) (\phi_{2d}^c i_{1d} + \phi_{2q}^c i_{1q})^{-\frac{1}{2}}
 \end{aligned}$$

上式において動作点近傍の微小変動を考えると次式のようになる。

$$\begin{aligned}
 &(p\widehat{\phi}_{2d})_0 + p\Delta \widehat{\phi}_{2d} \\
 &= \frac{\sqrt{M^*}}{2} \{ (i_{1d0} + \Delta i_{1d}) p(\phi_{2d0}^c + \Delta \phi_{2d}^c) + (\phi_{2d0}^c + \Delta \phi_{2d}^c) \\
 &\times p(i_{1d0} + \Delta i_{1d}) + (i_{1q0} + \Delta i_{1q}) p(\phi_{2q0}^c + \Delta \phi_{2q}^c) \\
 &+ (\phi_{2q0}^c + \Delta \phi_{2q}^c) p(i_{1q0} + \Delta i_{1q}) \} (\phi_{2d0}^c + \Delta \phi_{2d}^c) \\
 &\times (i_{1d0} + \Delta i_{1d}) + (\phi_{2q0}^c + \Delta \phi_{2q}^c) (i_{1q0} + \Delta i_{1q}) \}^{-\frac{1}{2}}
 \end{aligned}$$

微小変化分の積を零とし整理すると次のようになる。

$$\begin{aligned}
 &(p\widehat{\phi}_{2d})_0 + p\Delta \widehat{\phi}_{2d} \\
 &= \frac{\sqrt{M^*}}{2} \{ i_{1d0} p\Delta \phi_{2d}^c + \phi_{2d0}^c p\Delta i_{1d} + i_{1q0} p\Delta \phi_{2q}^c + \phi_{2q0}^c p\Delta i_{1q} \} \\
 &\times (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}} \{ 1 + (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-1} \\
 &\times (\phi_{2d0}^c \Delta i_{1d} + i_{1d0} \Delta \phi_{2d}^c + \phi_{2q0}^c \Delta i_{1q} + i_{1q0} \Delta \phi_{2q}^c) \}^{-\frac{1}{2}}
 \end{aligned}$$

上式の ()^{-1/2} 項において (1 + Δx)ⁿ ≃ 1 + nΔx の近似を行うと次のようになる。

$$\begin{aligned}
 &(p\widehat{\phi}_{2d})_0 + p\Delta \widehat{\phi}_{2d} \\
 &= \frac{\sqrt{M^*}}{2} \{ i_{1d0} p\Delta \phi_{2d}^c + \phi_{2d0}^c p\Delta i_{1d} + i_{1q0} p\Delta \phi_{2q}^c + \phi_{2q0}^c p\Delta i_{1q} \} \\
 &\times \{ (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}} \\
 &- \frac{1}{2} (\phi_{2d0}^c \Delta i_{1d} + i_{1d0} \Delta \phi_{2d}^c + \phi_{2q0}^c \Delta i_{1q} + i_{1q0} \Delta \phi_{2q}^c) \\
 &\times (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{3}{2}} \}
 \end{aligned}$$

上式を展開し微小変化分だけを取り出すと次式となる。

$$p\Delta\widehat{\phi}_{2d} = \frac{\sqrt{M^*}}{2}(i_{1d0}p\Delta\phi_{2d}^c + \phi_{2d0}^c p\Delta i_{1d} + i_{1q0}p\Delta\phi_{2q}^c + \phi_{2q0}^c p\Delta i_{1q})(\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}} \dots \dots \dots (43)$$

(43)式に(25)(26)(30)(31)式を代入し整理すると次式となる。

$$p\Delta\widehat{\phi}_{2d} = \frac{\sqrt{M^*}}{2}(\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})^{-\frac{1}{2}}(g_{21}\Delta i_{1d} + g_{22}\Delta i_{1q} + g_{23}\Delta i_{2d} + g_{24}\Delta i_{2q} + g_{25}\Delta\omega_r + g_{26}\Delta\phi_{2d}^c + g_{27}\Delta\phi_{2q}^c + g_{28}\Delta v_{sd} + g_{29}\Delta v_{sq}) \dots \dots \dots (44)$$

上式の係数 $g_{21} \sim g_{29}$ は次のようになる。

$$g_{21} = \phi_{2d0}^c \left(-\frac{R_1}{l}\right) + \phi_{2q0}^c \left\{ -\left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0}\right) \right. \\ \left. + i_{1d0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^*\right) + i_{1q0} \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \right. \\ g_{22} = \phi_{2d0}^c \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0}\right) + \phi_{2q0}^c \left(-\frac{R_1}{l}\right) \\ \left. + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM^2}{2L_2 l} \omega_{r0}\right) + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^*\right) \right. \\ g_{23} = \phi_{2d0}^c \frac{R_2 M}{L_2 l} + \phi_{2q0}^c \left(-\frac{PM}{2l} \omega_{r0}\right) + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l}\right) \\ \left. + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^* PM}{2l} \omega_{r0}\right) \right. \\ g_{24} = \phi_{2d0}^c \frac{PM}{2l} \omega_{r0} + \phi_{2q0}^c \frac{R_2 M}{L_2 l} + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM}{2l} \omega_{r0}\right) \\ \left. + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l}\right) \right. \\ g_{25} = \phi_{2d0}^c \frac{PM\phi_{2q0}}{2L_2 l} + \phi_{2q0}^c \left(-\frac{PM\phi_{2d0}}{2L_2 l}\right) \\ \left. + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM\phi_{2q0}}{2L_2 l}\right) + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^* PM\phi_{2d0}}{2L_2 l}\right) \right. \\ g_{26} = i_{1d0} \left(-\frac{1}{T_c}\right) + i_{1q0} (-\omega_{\phi 0}) \\ g_{27} = i_{1d0} \omega_{\phi 0} + i_{1q0} \left(-\frac{1}{T_c}\right) \\ g_{28} = \phi_{2d0}^c \frac{K_v}{l} + i_{1d0} \left(1 - \frac{l^*}{l}\right) \frac{L_2^*}{M^*} K_v \\ g_{29} = \phi_{2q0}^c \frac{K_v}{l} + i_{1q0} \left(1 - \frac{l^*}{l}\right) \frac{L_2^*}{M^*} K_v$$

上式において、 $g_{03} = \phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0}$ の置き換えを行

うと次式が得られる。

$$p\Delta\widehat{\phi}_{2d} = \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{21} \Delta i_{1d} + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{22} \Delta i_{1q} \\ + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{23} \Delta i_{2d} + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{24} \Delta i_{2q} \\ + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{25} \Delta\omega_r + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{26} \Delta\phi_{2d}^c \\ + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{27} \Delta\phi_{2q}^c + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28} \Delta v_{sd} \\ + \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29} \Delta v_{sq} \dots \dots \dots (45)$$

(14)式において、動作点近傍の微小変動を考えると、

$$(pi_{1d}^*)_0 + p\Delta i_{1d}^* = K_d \{ p\phi_{2d}^* + \phi_{2d}^*/\tau_d - p(\widehat{\phi}_{2d0} + \Delta\widehat{\phi}_{2d}) \\ - (\widehat{\phi}_{2d0} + \Delta\widehat{\phi}_{2d})/\tau_d \}$$

となる。上式の微小変化分だけを取り出すと次式となる。

$$p\Delta i_{1d}^* = -K_d \left(p\Delta\widehat{\phi}_{2d} + \frac{1}{\tau_d} \Delta\widehat{\phi}_{2d} \right)$$

上式に(42)(45)式を代入し整理すると次式が得られる。

$$p\Delta i_{1d}^* = -K_d \frac{\sqrt{M^*}}{2} (g_{03}^{-\frac{1}{2}} g_{21} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2d0}^c) \Delta i_{1d} \\ - K_d \frac{\sqrt{M^*}}{2} (g_{03}^{-\frac{1}{2}} g_{22} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2q0}^c) \Delta i_{1q} \\ - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{23} \Delta i_{2d} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{24} \Delta i_{2q} \\ - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{25} \Delta\omega_r \\ - K_d \frac{\sqrt{M^*}}{2} (g_{03}^{-\frac{1}{2}} g_{26} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1d0}) \Delta\phi_{2d}^c \\ - K_d \frac{\sqrt{M^*}}{2} (g_{03}^{-\frac{1}{2}} g_{27} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1q0}) \Delta\phi_{2q}^c \\ - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28} \Delta v_{sd} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29} \Delta v_{sq} \\ \dots \dots \dots (46)$$

2. 3. 8 dq同期軸上電流制御ループの式(15)(16)の線形化

(15)式において、動作点近傍での微小変動を考えると。

$$(pv_{sd})_0 + p\Delta v_{sd} \\ = K_i \{ p(i_{1d0}^* + \Delta i_{1d}^*) - p(i_{1d0} + \Delta i_{1d}) \} + \frac{K_t}{\tau_i} \{ (i_{1d0}^* + \Delta i_{1d}^*) \\ - (i_{1d0} + \Delta i_{1d}) \}$$

上式の微小変化分だけを取り出すと次式になる。

$$\begin{aligned}
 p\Delta v_{sd} = & K_i p\Delta i_{1d}^* - K_i p\Delta i_{1d} + \frac{K_i}{\tau_i} \Delta i_{1d}^* \Delta i_{1d} - \frac{K_i}{\tau_i} \\
 & \text{上式に (25) (46) 式を代入し整理すると次式が得られる。} \\
 p\Delta v_{sd} = & K_i \left\{ \frac{R_1}{l} - K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{21} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2d0}^c \right) - \frac{1}{\tau_i} \right\} \\
 & \times \Delta i_{1d} + K_i \left\{ - \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) - K_d \frac{\sqrt{M^*}}{2} \right. \\
 & \times \left(g_{03}^{-\frac{1}{2}} g_{22} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2q0}^c \right) \left. \right\} \Delta i_{1q} \\
 & + K_i \left(-\frac{R_2 M}{L_2 l} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{23} \right) \Delta i_{2d} \\
 & + K_i \left(-\frac{PM}{2l} \omega_{r0} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{24} \right) \Delta i_{2q} \\
 & + K_i \left(-\frac{PM \phi_{2q0}}{2L_2 l} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{25} \right) \Delta \omega_r \\
 & - K_i K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{26} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1d0} \right) \Delta \phi_{2d}^c \\
 & - K_i K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{27} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1q0} \right) \Delta \phi_{2q}^c \\
 & - K_i i_{1q0} \widehat{\Delta \omega}_r - K_i g_1 i_{1q0} \Delta i_{1q}^* + \frac{K_i}{\tau_i} \Delta i_{1d}^* \\
 & + K_i \left(-\frac{K_v}{l} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28} \right) \Delta v_{sd} \\
 & - K_i K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29} \Delta v_{sq} \dots \dots \dots (47)
 \end{aligned}$$

(16)式においても(15)式と同じ手順を踏み微小変化分を計算すると次式が得られる。

$$\begin{aligned}
 p\Delta v_{sq} = & K_i \left[\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} + K_q g_2 \left\{ (g_3 + g_{12}) \right. \right. \\
 & \left. \left. - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \right] \Delta i_{1d} + K_i \left[\frac{R_1}{l} + K_q g_2 \right. \\
 & \times \left\{ (g_4 + g_{13}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\} - \frac{1}{\tau_i} \left. \right] \Delta i_{1q} \\
 & + K_i \left\{ \frac{PM}{2l} \omega_{r0} + K_q g_2 (g_5 + g_{14}) \right\} \Delta i_{2d} \\
 & + K_i \left\{ -\frac{R_2 M}{L_2 l} + K_q g_2 (g_6 + g_{15}) \right\} \Delta i_{2q} \\
 & + K_i \left\{ \frac{PM \phi_{2d0}}{2L_2 l} + K_q g_2 (g_7 + g_{16}) \right\} \Delta \omega_r + K_i K_q g_2 \\
 & \times \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\}
 \end{aligned}$$

$$\begin{aligned}
 & \times \Delta \phi_{2d}^c + K_i K_q g_2 \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} \right. \right. \\
 & \left. \left. + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\} \Delta \phi_{2q}^c + K_i \left(i_{1d0} - \frac{K_q}{\tau_q} g_2 \right) \widehat{\Delta \omega}_r \\
 & + K_i \left(g_1 i_{1d0} - \frac{K_q}{\tau_\omega} g_2 + \frac{1}{\tau_i} \right) \Delta i_{1q}^* + K_i K_q g_2 \\
 & \times (g_{10} + g_{19}) \Delta v_{sd} + K_i \left\{ -\frac{K_v}{l} + g_2 K_q (g_{11} + g_{20}) \right\} \\
 & \times \Delta v_{sq} + K_i \frac{K_q}{1 + K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) \Delta \omega_r^* \dots \dots \dots (48)
 \end{aligned}$$

2. 3. 9 線形化モデル

得られた線形化微分方程式(25)～(31), (40) (41), (46)～(48)の12式をまとめると次式で表すことができる。

$$p\Delta x = A\Delta x + B\Delta \omega_r^* \dots \dots \dots (49)$$

ただし, 状態変数 Δx は次のようになる。

$$\Delta x = [\Delta i_{1d}, \Delta i_{1q}, \Delta i_{2d}, \Delta i_{2q}, \Delta \omega_r, \Delta \phi_{2d}^c, \Delta \phi_{2q}^c, \widehat{\Delta \omega}_r, \Delta i_{1q}^*, \Delta i_{1d}^*, \Delta v_{sd}, \Delta v_{sq}]^T$$

3. 速度の伝達関数

電動機を速度を出力すると,

$$\Delta \omega_r = C\Delta x \dots \dots \dots (50)$$

ただし,

$$C = [0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0]$$

したがって, 速度指令 $\Delta \omega_r^*$ に対する速度 $\Delta \omega_r$ の伝達関数は次式より求まる。

$$\frac{\Delta \omega_r(s)}{\Delta \omega_r^*(s)} = \frac{d_3 \det(SI - A_3^*)}{s^3 \det(SI - A)} \dots \dots \dots (51)$$

ここで,

$$A_3^* = A - \frac{1}{d_3} BC, \quad d_3 = CAB$$

A, B については付録1を参照。また, 数式の共通部分を同じ記号に置き換えると三相静止軸上電流制御ループを用いた速度センサレスベクトル制御系の A も簡単化されたので, 付録においてその導出過程及び結果を示した。

4. まとめ

dq 同期軸上電流制御ループを用いた速度センサレスベクトル制御系を記述する非線形連立微分方程式を導出した。その非線形連立微分方程式を微小変位理論を用い線形化し線形化モデルを導出した。得られた線形化モデルから速度の伝達関数を導出した。付録2に

において、三相静止軸上電流制御ループを用いた速度センサレスベクトル制御系の非線形連立方程式、線形化モデル、速度の伝達関数を示した。

今後は、得られた伝達関数を用いて極と零点及び過渡応答を計算し、誘導電動機定数、制御回路定数がそれぞれの系に与える影響を検討する予定である。

文 献

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付 録

1. dq同期軸上電流制御ループを用いた速度センサレスベクトル制御系における A, B

$$A = \begin{array}{c} \begin{array}{cccccccccccc} a_{11} & a_{12} & a_{13} & a_{14} & g_{01} M \phi_{2q0} & 0 & 0 & i_{1q0} & g_1 i_{1q0} & 0 & \frac{K_v}{l} & 0 \\ -a_{12} & a_{11} & -a_{14} & a_{13} & -g_{01} M \phi_{2d0} & 0 & 0 & -i_{1d0} & -g_1 i_{1d0} & 0 & 0 & \frac{K_v}{l} \\ a_{31} & a_{32} & a_{33} & a_{34} & -g_{01} L_1 \phi_{2q0} & 0 & 0 & i_{2q0} & g_1 i_{2q0} & 0 & -\frac{MK_v}{L_2 l} & 0 \\ -a_{32} & a_{31} & -a_{34} & a_{33} & g_{01} L_1 \phi_{2d0} & 0 & 0 & -i_{2d0} & -g_1 i_{2d0} & 0 & 0 & -\frac{MK_v}{L_2 l} \\ -\frac{PM}{2J} i_{2q0} & \frac{PM}{2J} i_{2d0} & \frac{PM}{2J} i_{1q0} & -\frac{PM}{2J} i_{1d0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{61} & a_{62} & a_{63} & a_{64} & -\frac{L_2^*}{M^*} l^* g_{01} M \phi_{2q0} & -\frac{1}{T_c^*} & \omega_{\phi 0} & \phi_{2q0}^c & g_1 \phi_{2q0}^c & 0 & a_{6,11} & 0 \\ -a_{62} & a_{61} & -a_{64} & a_{63} & \frac{L_2^*}{M^*} l^* g_{01} M \phi_{2d0} & -\omega_{\phi 0} & -\frac{1}{T_c^*} & -\phi_{2d0}^c & -g_1 \phi_{2d0}^c & 0 & 0 & a_{6,11} \\ a_{81} & a_{82} & a_{83} & a_{84} & a_{85} & a_{86} & a_{87} & a_{88} & a_{89} & 0 & a_{8,11} & a_{8,12} \\ -K_q a_{81} & -K_q a_{82} & -K_q a_{83} & -K_q a_{84} & -K_q a_{85} & -K_q a_{86} & -K_q a_{87} & \frac{a_{88}}{K_\omega} & -K_q a_{89} & 0 & -K_q a_{8,11} & -K_q a_{8,12} \\ a_{10,1} & a_{10,2} & a_{10,3} & a_{10,4} & a_{10,5} & a_{10,6} & a_{10,7} & 0 & 0 & 0 & a_{10,11} & a_{10,12} \\ a_{11,1} & a_{11,2} & a_{11,3} & a_{11,4} & a_{11,5} & a_{11,6} & a_{11,7} & -K_t i_{1q0} & -K_t g_1 i_{1q0} & \frac{K_t}{\tau_i} & a_{11,11} & a_{11,12} \\ a_{12,1} & a_{12,2} & a_{12,3} & a_{12,4} & a_{12,5} & a_{12,6} & a_{12,7} & a_{12,8} & a_{12,9} & 0 & a_{12,11} & a_{12,12} \end{array} \end{array}$$

$$B^T = \begin{array}{c} \begin{array}{cccccccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{K_\omega K_q}{1+K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) & \frac{K_q}{1+K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) & 0 & 0 & \frac{K_t K_q}{1+K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) & & & \end{array} \end{array}$$

ここで,

$$g_1 = \frac{M^* R_2^*}{L_2^* \phi_{2d}^*}$$

$$g_2 = \frac{K_\omega}{1 + K_\omega K_q}$$

$$l = \frac{L_1 L_2 - M^2}{L_2}$$

$$l^* = \frac{L_1^* L_2^* - M^{*2}}{L_2^*}$$

$$\omega_{\phi 0} = \widehat{\omega_{r0}} + g_1 i_{1q0}^*$$

$$\omega_{s0} = \omega_{\phi 0} - \frac{P}{2} \omega_{r0}$$

$$\widehat{\phi_{2d0}} = \sqrt{M^* (\phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0})}$$

$$|\phi_{20}^c| = \sqrt{\phi_{2d0}^{c2} + \phi_{2q0}^{c2}}$$

$$\phi_{2d0} = M i_{1d0} + L_2 i_{2d0}$$

$$\phi_{2q0} = M i_{1q0} + L_2 i_{2q0}$$

$$\widehat{i_{1q0}} = \frac{\phi_{2d0}^c i_{1q0} - \phi_{2q0}^c i_{1d0}}{|\phi_{20}^c|}$$

$$g_{01} = \frac{P}{2L_2 l}$$

$$g_{02} = \phi_{2q0}^c i_{1d0} - \phi_{2d0}^c i_{1q0}$$

$$g_{03} = \phi_{2d0}^c i_{1d0} + \phi_{2q0}^c i_{1q0}$$

$$g_3 = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \left(-\frac{R_1}{l} \right) - \phi_{2d0}^c \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) - i_{1d0} \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \right\}$$

$$g_4 = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) + \phi_{2d0}^c \left(-\frac{R_1}{l} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM^2}{2L_2 l} \omega_{r0} \right) - i_{1d0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \right\}$$

$$g_5 = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{R_2 M}{L_2 l} + \phi_{2d0}^c \left(-\frac{PM}{2l} \omega_{r0} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) - i_{1d0} \frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0} \right\}$$

$$g_6 = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{PM}{2l} \omega_{r0} + \phi_{2d0}^c \left(\frac{R_2 M}{L_2 l} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM}{2l} \omega_{r0} \right) - i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) \right\}$$

$$g_7 = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{PM \phi_{2q0}}{2L_2 l} + \phi_{2d0}^c \left(-\frac{PM \phi_{2d0}}{2L_2 l} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM \phi_{2q0}}{2L_2 l} \right) - i_{1d0} \frac{L_2^*}{M^*} \frac{l^* PM \phi_{2d0}}{2L_2 l} \right\}$$

$$g_8 = \frac{1}{|\phi_{20}^c|} \left\{ i_{1q0} \left(-\frac{1}{T_c^*} \right) - i_{1d0} (-\omega_{\phi 0}) \right\}$$

$$g_9 = \frac{1}{|\phi_{20}^c|} \left\{ i_{1q0} \omega_{\phi 0} - i_{1d0} \left(-\frac{1}{T_c^*} \right) \right\}$$

$$g_{10} = \frac{1}{|\phi_{20}^c|} \left\{ -\phi_{2q0}^c \frac{K_v}{l} + i_{1q0} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \right\}$$

$$g_{11} = \frac{1}{|\phi_{20}^c|} \left\{ \phi_{2d0}^c \frac{K_v}{l} - i_{1d0} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \right\}$$

$$g_{12} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \right\}$$

$$g_{13} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* PM^2}{2L_2 l} \omega_{r0} \right) + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \right\}$$

$$g_{14} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0} \right\}$$

$$g_{15} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* PM}{2l} \omega_{r0} \right) + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) \right\}$$

$$g_{16} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \frac{L_2^*}{M^*} \left(-\frac{l^* PM \phi_{2q0}}{2L_2 l} \right) + \phi_{2q0}^c g_{02} \frac{L_2^*}{M^*} \left(\frac{l^* PM \phi_{2d0}}{2L_2 l} \right) \right\}$$

$$g_{17} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \left(-\frac{1}{T_c^*} \right) + \phi_{2q0}^c g_{02} (-\omega_{\phi 0}) \right\}$$

$$g_{18} = \frac{1}{|\phi_{20}^c|^3} \left\{ \phi_{2d0}^c g_{02} \omega_{\phi 0} + \phi_{2q0}^c g_{02} \left(-\frac{1}{T_c^*} \right) \right\}$$

$$g_{19} = \frac{1}{|\phi_{20}^c|^3} \phi_{2d0}^c g_{02} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v$$

$$g_{20} = \frac{1}{|\phi_{20}^c|^3} \phi_{2q0}^c g_{02} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v$$

$$g_{21} = \phi_{2d0}^c \left(-\frac{R_1}{l} \right) + \phi_{2q0}^c \left\{ -\left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) + i_{1d0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) + i_{1q0} \frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0} \right\}$$

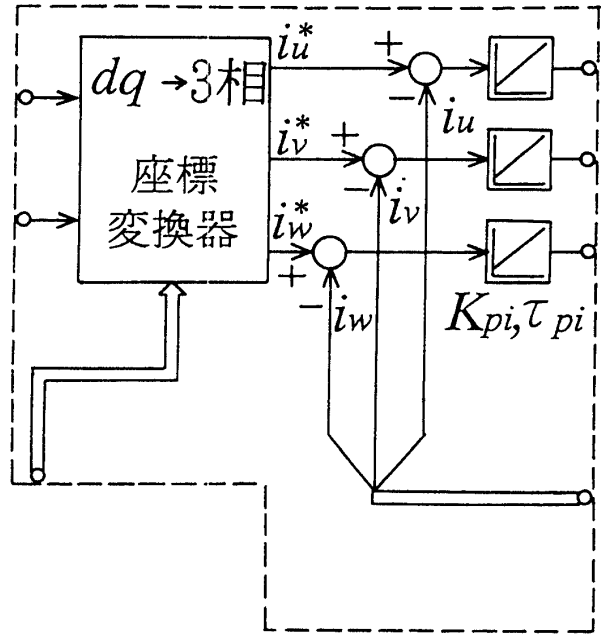
$$\begin{aligned}
g_{22} &= \phi_{2d0}^c \left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) + \phi_{2q0}^c \left(-\frac{R_1}{l} \right) \\
&\quad + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM^2}{2L_2 l} \omega_{r0} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \\
g_{23} &= \phi_{2d0}^c \frac{R_2 M}{L_2 l} + \phi_{2q0}^c \left(-\frac{PM}{2l} \omega_{r0} \right) \\
&\quad + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^* PM}{2l} \omega_{r0} \right) \\
g_{24} &= \phi_{2d0}^c \frac{PM}{2l} \omega_{r0} + \phi_{2q0}^c \frac{R_2 M}{L_2 l} + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM}{2l} \omega_{r0} \right) \\
&\quad + i_{1q0} \frac{L_2^*}{M^*} \left(-\frac{l^* R_2 M}{L_2 l} \right) \\
g_{25} &= \phi_{2d0}^c \frac{PM \phi_{2q0}}{2L_2 l} + \phi_{2q0}^c \left(-\frac{PM \phi_{2d0}}{2L_2 l} \right) \\
&\quad + i_{1d0} \frac{L_2^*}{M^*} \left(-\frac{l^* PM \phi_{2q0}}{2L_2 l} \right) + i_{1q0} \frac{L_2^*}{M^*} \left(\frac{l^* PM \phi_{2d0}}{2L_2 l} \right) \\
g_{26} &= i_{1d0} \left(-\frac{1}{\Gamma_c^*} \right) + i_{1q0} (-\omega_{\phi 0}) \\
g_{27} &= i_{1d0} \omega_{\phi 0} + i_{1q0} \left(-\frac{1}{\Gamma_c^*} \right) \\
g_{28} &= \phi_{2d0}^c \frac{K_v}{l} + i_{1d0} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \\
g_{29} &= \phi_{2q0}^c \frac{K_v}{l} + i_{1q0} \left(1 - \frac{l^*}{l} \right) \frac{L_2^*}{M^*} K_v \\
a_{11} &= -\frac{R_1}{l} \\
a_{12} &= \omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \\
a_{13} &= \frac{R_2 M}{L_2 l} \\
a_{14} &= \frac{PM}{2l} \omega_{r0} \\
a_{31} &= \frac{R_1 M}{L_2 l} \\
a_{32} &= -\frac{PL_1 M}{2L_2 l} \omega_{r0} \\
a_{33} &= -\frac{R_2 L_1}{L_2 l} \\
a_{34} &= \omega_{\phi 0} - \frac{PL_1}{2l} \omega_{r0} \\
a_{61} &= \frac{L_2^*}{M^*} \left(\frac{l^*}{l} R_1 - R_1^* \right) \\
a_{62} &= -\frac{L_2^*}{M^*} \frac{l^*}{2} \frac{PM^2}{L_2 l} \omega_{r0} \\
a_{63} &= -\frac{L_2^*}{M^*} \frac{l^* R_2 M}{L_2 l}
\end{aligned}$$

$$\begin{aligned}
a_{64} &= -\frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0} \\
a_{6,11} &= \frac{L_2^*}{M^*} \left(1 - \frac{l^*}{l} \right) K_v \\
a_{81} &= -g_2 \left\{ (g_3 + g_{12}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \\
a_{82} &= -g_2 \left\{ (g_4 + g_{13}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \\
a_{83} &= -g_2 (g_5 + g_{14}) \\
a_{84} &= -g_2 (g_6 + g_{15}) \\
a_{85} &= -g_2 (g_7 + g_{16}) \\
a_{86} &= -g_2 \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\} \\
a_{87} &= -g_2 \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\} \\
a_{88} &= -\frac{K_q}{\tau_q} g_2 \\
a_{89} &= \frac{g_2}{\tau_\omega} \\
a_{8,11} &= -g_2 (g_{10} + g_{19}) \\
a_{8,12} &= -g_2 (g_{11} + g_{20}) \\
a_{10,1} &= -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{21} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2d0}^c \right) \\
a_{10,2} &= -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{22} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2q0}^c \right) \\
a_{10,3} &= -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{23} \\
a_{10,4} &= -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{24} \\
a_{10,5} &= -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{25} \\
a_{10,6} &= -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{26} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1d0} \right) \\
a_{10,7} &= -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{27} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1q0} \right) \\
a_{10,11} &= -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28} \\
a_{10,12} &= -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29} \\
a_{11,1} &= K_i \left\{ \frac{R_1}{l} - K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{21} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2d0}^c \right) - \frac{1}{\tau_i} \right\} \\
a_{11,2} &= K_i \left\{ -\left(\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} \right) \right. \\
&\quad \left. - K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{22} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2q0}^c \right) \right\}
\end{aligned}$$

$$\begin{aligned}
 a_{11.3} &= K_i \left(-\frac{R_2 M}{L_2 l} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{23} \right) \\
 a_{11.4} &= K_i \left(-\frac{PM}{2l} \omega_{r0} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{24} \right) \\
 a_{11.5} &= K_i \left(-\frac{PM\phi_{2q0}}{2L_2 l} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{25} \right) \\
 a_{11.6} &= -K_i K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{26} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1d0} \right) \\
 a_{11.7} &= -K_i K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{27} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1q0} \right) \\
 a_{11.11} &= K_i \left(-\frac{K_v}{l} - K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28} \right) \\
 a_{11.12} &= -K_i K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29} \\
 a_{12.1} &= K_i \left[\omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0} + K_q g_2 \left\{ (g_3 + g_{12}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\} \right] \\
 a_{12.2} &= K_i \left[\frac{R_1}{l} + K_q g_2 \left\{ (g_4 + g_{13}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} - \frac{1}{\tau_i} \right\} \right] \\
 a_{12.3} &= K_i \left\{ \frac{PM}{2l} \omega_{r0} + K_q g_2 (g_5 + g_{14}) \right\} \\
 a_{12.4} &= K_i \left\{ -\frac{R_2 M}{L_2 l} + K_q g_2 (g_6 + g_{15}) \right\} \\
 a_{12.5} &= K_i \left\{ \frac{PM\phi_{2d0}}{2L_2 l} + K_q g_2 (g_7 + g_{16}) \right\} \\
 a_{12.6} &= K_i K_q g_2 \left\{ (g_8 + g_{17}) \right. \\
 &\quad \left. + \frac{1}{\tau_\omega} \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\} \\
 a_{12.7} &= K_i K_q g_2 \left\{ (g_9 + g_{18}) \right. \\
 &\quad \left. + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\} \\
 a_{12.8} &= K_i \left(i_{1d0} - \frac{K_q}{\tau_q K_\omega} g_2 \right) \\
 a_{12.9} &= K_i \left(g_1 i_{1d0} - \frac{K_q}{\tau_q} g_2 + \frac{1}{\tau_i} \right) \\
 a_{12.11} &= K_i K_q g_2 (g_{10} + g_{19}) \\
 a_{12.12} &= K_i \left\{ -\frac{K_v}{l} + g_2 K_q (g_{11} + g_{20}) \right\}
 \end{aligned}$$

2. 三相静止軸上電流制御ループを用いた速度センサレスベクトル制御系の線形化モデル

三相静止軸上電流制御ループの式は次式で表される⁽¹⁾。



付図1 三相静止軸上電流制御ループ

$$pA_d = -(K_{pi}/\tau_{pi})(i_{1d}^* - i_{1d}) - B_d \dots\dots\dots (付1)$$

$$pA_q = -(K_{pi}/\tau_{pi})(i_{1q}^* - i_{1q}) - B_q \dots\dots\dots (付2)$$

$$pB_d = (K_{pi}/\tau_{pi})\{\omega_\phi(i_{1q}^* - i_{1q}) + p\omega_\phi C_q\} + \omega_\phi^2 A_d \dots\dots (付3)$$

$$pB_q = -(K_{pi}/\tau_{pi})\{\omega_\phi(i_{1d}^* - i_{1d}) - p\omega_\phi C_d\} + \omega_\phi^2 A_q \dots\dots\dots (付4)$$

$$pC_d = -(i_{1d}^* - i_{1d}) - \omega_\phi C_q \dots\dots\dots (付5)$$

$$pC_q = (i_{1q}^* - i_{1q}) + \omega_\phi C_d \dots\dots\dots (付6)$$

$$v_{1d} = K_v (K_{pi}(i_{1d}^* - i_{1d}) - A_d)$$

$$v_{1q} = K_v (K_{pi}(i_{1q}^* - i_{1q}) - A_q)$$

従って、三相静止軸上電流制御ループを用いた速度センサレスベクトル制御系は(5)～(11)，(付1)～(付6)式で記述される。それぞれの式をdq同期軸上電流制御ループを用いた場合と同様に線形化すると(49)式と同じ形で表わすことができる。ただし状態変数 Δx は次のようになる。

$$\Delta x = [\Delta i_{1d}, \Delta i_{1q}, \Delta i_{2d}, \Delta i_{2q}, \Delta \omega_r, \Delta \phi_{2d}^c, \Delta \phi_{2q}^c, \Delta \hat{\omega}_r, \Delta i_{1q}^*, \Delta i_{1d}^*, \Delta A_d, \Delta A_q, \Delta B_d, \Delta B_q, \Delta C_d, \Delta C_q]^T$$

また、電動機を速度を出力すると(50)式で表わすことができる。ただし、 C は次のようになる。

$$C = [0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]$$

従って、速度の伝達関数は(51)式で表わすことができる。 A 、 B は付録1の置き換えを用いると次のようになる。

$$A = \begin{matrix} \begin{matrix} a_{11} & a_{12} & a_{13} & a_{14} & g_{01} M \phi_{2q0} & 0 & 0 & i_{1q0} & g_1 i_{1q0} & \frac{K_v K_{pi}}{l} \\ -a_{12} & a_{11} & -a_{14} & a_{13} & -g_{01} M \phi_{2d0} & 0 & 0 & -i_{1d0} & -g_1 i_{1d0} + \frac{K_v K_{pi}}{l} & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & -g_{01} L_1 \phi_{2q0} & 0 & 0 & i_{2q0} & g_1 i_{2q0} & -\frac{MK_v K_{pi}}{L_2 l} \\ -a_{32} & a_{31} & -a_{34} & a_{33} & g_{01} L_1 \phi_{2d0} & 0 & 0 & -i_{2d0} & -g_1 i_{2d0} - \frac{MK_v K_{pi}}{L_2 l} & 0 \\ -\frac{PM}{2J} i_{2q0} & \frac{PM}{2J} i_{2d0} & \frac{PM}{2J} i_{1q0} & -\frac{PM}{2J} i_{1d0} & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{61} & a_{62} & a_{63} & a_{64} & -\frac{L_2^*}{M^*} l^* g_{01} M \phi_{2q0} & -\frac{1}{T_c^*} & \omega_{\phi 0} & \phi_{2q0}^c & g_1 \phi_{2q0}^c & a_{6,10} \\ -a_{62} & a_{61} & -a_{64} & a_{63} & \frac{L_2^*}{M^*} l^* g_{01} M \phi_{2d0} & -\omega_{\phi 0} & -\frac{1}{T_c^*} & -\phi_{2d0}^c & -g_1 \phi_{2d0}^c + a_{6,10} & 0 \\ a_{81} & a_{82} & a_{83} & a_{84} & a_{85} & a_{86} & a_{87} & a_{88} & a_{89} & a_{8,10} \\ -K_q a_{81} & -K_q a_{82} & -K_q a_{83} & -K_q a_{84} & -K_q a_{85} & -K_q a_{86} & -K_q a_{87} & a_{88}/K_\omega & -K_q a_{89} & -K_q a_{8,10} \\ a_{10,1} & a_{10,2} & a_{10,3} & a_{10,4} & a_{10,5} & a_{10,6} & a_{10,7} & 0 & a_{10,9} & a_{10,10} \\ K_{pi}/\tau_{pi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{pi}/\tau_{pi} \\ 0 & K_{pi}/\tau_{pi} & 0 & 0 & 0 & 0 & 0 & 0 & -K_{pi}/\tau_{pi} & 0 \\ a_{13,1} & a_{13,2} & a_{13,3} & a_{13,4} & a_{13,5} & a_{13,6} & a_{13,7} & a_{13,8} & a_{13,9} & a_{13,10} \\ a_{14,1} & a_{14,2} & a_{14,3} & a_{14,4} & a_{14,5} & a_{14,6} & a_{14,7} & a_{14,8} & a_{14,9} & a_{14,10} \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -C_{q0} & -g_1 C_{q0} & -1 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & C_{d0} & 1 + g_1 C_{d0} & 0 \end{matrix} \\ \end{matrix} \quad *$$

$$* \begin{matrix} \begin{matrix} -\frac{K_v}{l} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_v}{l} & 0 & 0 & 0 & 0 \\ \frac{MK_v}{L_2 l} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{MK_v}{L_2 l} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ a_{6,11} & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{6,11} & 0 & 0 & 0 & 0 \\ a_{8,11} & a_{8,12} & 0 & 0 & 0 & 0 \\ -K_q a_{8,11} & -K_q a_{8,12} & 0 & 0 & 0 & 0 \\ a_{10,11} & a_{10,12} & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ a_{13,11} & a_{13,12} & 0 & 0 & 0 & 0 \\ a_{14,11} & a_{14,12} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\omega_{\phi 0} \\ 0 & 0 & 0 & 0 & \omega_{\phi 0} & 0 \end{matrix} \end{matrix}$$

$$\mathbf{B}^T = \begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|} \hline 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{K_\omega K_q}{1+K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) & \frac{K_q}{1+K_\omega K_q} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) & 0 & 0 & 0 \\ \hline \end{array} *$$

$$* \begin{array}{|c|c|c|c|} \hline \frac{K_{p_i} K_q}{\tau_{p_i} (1+K_\omega K_q)} C_{q0} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) (K_\omega + g_1) & \frac{K_{p_i} K_q}{\tau_{p_i} (1+K_\omega K_q)} C_{d0} \frac{P}{2} \left(p + \frac{1}{\tau_q} \right) (K_\omega + g_1) & 0 & 0 \\ \hline \end{array}$$

ここで,

$$a_{11} = -\frac{R_1 + K_v K_{p_i}}{l}$$

$$a_{12} = \omega_{\phi 0} + \frac{PM^2}{2L_2 l} \omega_{r0}$$

$$a_{13} = \frac{R_2 M}{L_2 l}$$

$$a_{14} = \frac{PM}{2l} \omega_{r0}$$

$$a_{31} = \frac{M(R_1 + K_v K_{p_i})}{L_2 l}$$

$$a_{32} = -\frac{PL_1 M}{2L_2 l} \omega_{r0}$$

$$a_{33} = -\frac{R_2 L_1}{L_2 l}$$

$$a_{34} = \omega_{\phi 0} - \frac{PL_1}{2l} \omega_{r0}$$

$$a_{61} = \frac{L_2^*}{M^*} \left\{ \frac{l^*}{l} R_1 - R_1^* - \left(1 - \frac{l^*}{l} \right) K_v K_{p_i} \right\}$$

$$a_{62} = -\frac{L_2^*}{M^*} \frac{l^* PM^2}{2L_2 l} \omega_{r0}$$

$$a_{63} = -\frac{L_2^*}{M^*} \frac{l^* R_2 M}{L_2 l}$$

$$a_{64} = -\frac{L_2^*}{M^*} \frac{l^* PM}{2l} \omega_{r0}$$

$$a_{6,10} = \frac{L_2^*}{M^*} K_v K_{p_i} \left(1 - \frac{l^*}{l} \right)$$

$$a_{6,11} = -\frac{L_2^*}{M^*} K_v \left(1 - \frac{l^*}{l} \right)$$

$$a_{81} = -g_2 \left\{ (g_3 + g_{12}) - K_{p_i} (g_{10} + g_{19}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\}$$

$$a_{82} = -g_2 \left\{ (g_4 + g_{13}) - K_{p_i} (g_{11} + g_{20}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\}$$

$$a_{83} = -g_2 (g_5 + g_{14})$$

$$a_{84} = -g_2 (g_6 + g_{15})$$

$$a_{85} = -g_2 (g_7 + g_{16})$$

$$a_{86} = -g_2 \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\}$$

$$a_{87} = -g_2 \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\}$$

$$a_{88} = -\frac{K_q}{\tau_q} g_2$$

$$a_{89} = -g_2 \left\{ K_{p_i} (g_{11} + g_{20}) - \frac{1}{\tau_\omega} \right\}$$

$$a_{8,10} = -K_{p_i} g_2 (g_{10} + g_{19})$$

$$a_{8,11} = g_2 (g_{10} + g_{19})$$

$$a_{8,12} = g_2 (g_{11} + g_{20})$$

$$a_{10,3} = -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{23}$$

$$a_{10,4} = -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{24}$$

$$a_{10,5} = -K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{25}$$

$$a_{10,1} = -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{21} - K_{p_i} g_{03}^{-\frac{1}{2}} g_{28} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2d0}^c \right)$$

$$a_{10,2} = -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{22} - K_{p_i} g_{03}^{-\frac{1}{2}} g_{29} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} \phi_{2q0}^c \right)$$

$$a_{10,6} = -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{26} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1d0} \right)$$

$$a_{10,7} = -K_d \frac{\sqrt{M^*}}{2} \left(g_{03}^{-\frac{1}{2}} g_{27} + \frac{1}{\tau_d} g_{03}^{-\frac{1}{2}} i_{1q0} \right)$$

$$a_{10,9} = -K_{p_i} K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29}$$

$$a_{10,10} = -K_{p_i} K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28}$$

$$a_{10,11} = K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{28}$$

$$a_{10,12} = K_d \frac{\sqrt{M^*}}{2} g_{03}^{-\frac{1}{2}} g_{29}$$

$$a_{13,1} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) \times \left\{ (g_3 + g_{12}) - K_{pi} (g_{10} + g_{19}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\}$$

$$a_{13,2} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) \times \left\{ (g_4 + g_{13}) - K_{pi} (g_{11} + g_{20}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\}$$

$$a_{13,3} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) (g_5 + g_{14})$$

$$a_{13,4} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) (g_6 + g_{15})$$

$$a_{13,5} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) (g_7 + g_{16})$$

$$a_{13,6} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) \times \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\}$$

$$a_{13,7} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) \times \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\}$$

$$a_{13,8} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} \frac{K_q}{\tau_q} \left(1 + \frac{1}{K_\omega} g_1 \right) + \frac{K_{pi}}{\tau_{pi}} (i_{1q0}^* - i_{1q0}) + 2\omega_{\phi 0} A_{d0}$$

$$a_{13,9} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) \left\{ K_{pi} (g_{11} + g_{20}) - \frac{1}{\tau_\omega} \right\} + \frac{K_{pi}}{\tau_{pi}} \{ g_1 (i_{1q0}^* - i_{1q0}) + \omega_{\phi 0} \} + 2\omega_{\phi 0} A_{d0} g_1$$

$$a_{13,10} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) K_{pi} (g_{10} + g_{19})$$

$$a_{13,11} = \frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) (g_{10} + g_{19}) + \omega_{\phi 0}^2$$

$$a_{13,12} = \frac{K_{pi}}{\tau_{pi}} g_2 C_{q0} (1 - K_q g_1) (g_{11} + g_{20})$$

$$a_{14,1} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) \times \left\{ (g_3 + g_{12}) - K_{pi} (g_{10} + g_{19}) - \frac{\phi_{2q0}^c}{\tau_\omega |\phi_{20}^c|} \right\} + \frac{K_{pi}}{\tau_{pi}} \omega_{\phi 0}$$

$$a_{14,2} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) \times \left\{ (g_4 + g_{13}) - K_{pi} (g_{11} + g_{20}) + \frac{\phi_{2d0}^c}{\tau_\omega |\phi_{20}^c|} \right\}$$

$$a_{14,3} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) (g_5 + g_{14})$$

$$a_{14,4} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) (g_6 + g_{15})$$

$$a_{14,5} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) (g_7 + g_{16})$$

$$a_{14,6} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) \times \left\{ (g_8 + g_{17}) + \frac{1}{\tau_\omega} \left(\frac{1}{|\phi_{20}^c|} i_{1q0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2d0}^c \right) \right\}$$

$$a_{14,7} = -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) \times \left\{ (g_9 + g_{18}) + \frac{1}{\tau_\omega} \left(-\frac{1}{|\phi_{20}^c|} i_{1d0} + \frac{1}{|\phi_{20}^c|^3} g_{02} \phi_{2q0}^c \right) \right\}$$

$$a_{14,8} = \left\{ -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} \frac{K_q}{\tau_q} \left(1 + \frac{1}{K_\omega} g_1 \right) - \frac{K_{pi}}{\tau_{pi}} (i_{1d0}^* - i_{1d0}) + 2\omega_{\phi 0} A_{q0} \right\}$$

$$a_{14,9} = \left\{ -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) \left\{ K_{pi} (g_{11} + g_{20}) - \frac{1}{\tau_\omega} \right\} - \frac{K_{pi}}{\tau_{pi}} g_1 (i_{1d0}^* - i_{1d0}) + 2\omega_{\phi 0} A_{q0} g_1 \right\}$$

$$a_{14,10} = \left\{ -\frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) K_{pi} (g_{10} + g_{19}) - \frac{K_{pi}}{\tau_{pi}} \omega_{\phi 0} \right\}$$

$$a_{14,11} = \frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) (g_{10} + g_{19})$$

$$a_{14,12} = \left\{ \frac{K_{pi}}{\tau_{pi}} g_2 C_{d0} (1 - K_q g_1) (g_{11} + g_{20}) + \omega_{\phi 0}^2 \right\}$$