狀態變數에 의한 回轉型電磁增幅機의 動特性 解析 및 減磁作用効果에 관한 硏究

논 문
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On The Dynamics and the Demagnetization Effect of the Amplidyne Generator with Auxiliary Feedback Compensating Winding

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Abstract

This work intends to study the machine dynamics in the state-space approach and to formulate the operating characteristics of an amplidyne generator, with balanced control field winding and an auxiliary feedback winding for compensating purpose. In the derivation of the dynamic equation, investigations on the demagnetization effects are accentuated, based on the magnetic interlinks between windings of the machine.

From the machine dynamic relation obtained, a state-variable representation of the machine dynamics is approached in the first part of this work.

1. Introduction

Even with it's large volumic size, the rotary electro-magnetic amplifiers have still certain advantages over the others in the field of power amplification for control purposes and they play considerable roles in many fields of control systems. This work is concerned to investigate the machine dynamics under the demagnetization effect by load current and to formulate the state-space model of the machine under these conditions. As a preliminary step to study external compensating schemes through an auxilirary feedback winding provided, the amplidyne generator is assumed to have a balanced control winding and an auxiliary feedback winding for the compensating purpose.

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In the early years of 1940 to 1950, extensive works had been focused on the study of the DC control machine under static and dynamic conditions of the machine and most of them discussed the problems under free-conditions from the demagnetization effect. Furthermore, the recent trends of control theory necessiate the adequate formulation of the state model of control components or systems so that modern control theories and optimization techniques of the system could be advantageously applicable in the time-domain approaches.

In the first part of this work, the machine parameters are assumed to be linear and time-invariant, and the demagnetization flux is assumed directly proportional to the causing current. For the amplidyne generators, two independent demagnetization effects are encountered by load current. One of these is from the resultant decrement in the direct-axis flux (this shall be called the primary demagnetization effect) and the other results from the decrement in the quadrature-axis component of the magnetic flux. The later shall be called the secondary demagnetization effect.

In deriving the dynamic equation, both of these demagnetization effects and their influencies upon the machine dynamics are investigated and accentuated throughout.

2. Distribution of Magnetic Flux in the Machine

The equivalent circuit of the machine with the auxiliary feedback winding, and with the balanced control winding is shown below, including the possible pronounced factors on the dynamic performance of the machine.

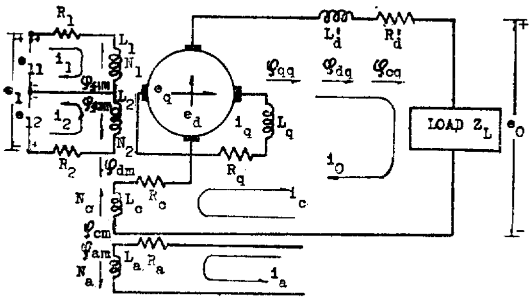

그림 1. 기계의 등가전기회로

Fig. 1. Equivalent Circuit of the Machine

It is the common practice and well understood, for the amplidyne generator, to set the brushes onto the geometrical neutral points and the main field-flux may not be affected pronouncedly by load current, although the flux distribution under the main control field may be distorted by the armature reaction effect, the net field-flux will remain constant except when the machine is under heavy load or transient conditions.

Since this work is concerned to the operation of the machine under these conditions, the demagnetization effect should be included, herewith.

If the machine is assumed not to be over-driven into the region of it's magnetic saturation and the machine operation is confined into this linear region (even though this is not necessarily required restriction for the theoretical development, this assumption shall be kept for a while), the armature MMF is assumed to be directly proportional to the load current.

The armature MMF due to the load current increases the flux density or magnetizes one side of each machine pole piece and demagnetizes the other side. The leading sides of the pole piece are easily saturated due to the magnetizing effect of the load current and it results the decrease in the main field flux. This component of the flux is denoted by φ_{dm} in figure 1. It may be reasonable to assume that this flux is proportional to the load current, i_0.

The direct-axis components of the magnetic flux can be expressible as being composed of;

$$\dot{\varphi}_f=\dot{\varphi}_{f1m}+\dot{\varphi}_{f2m}+\dot{\varphi}_{qm}+\dot{\varphi}_{dm}+\dot{\varphi}_{cm}+\dot{\varphi}_{am} \qquad (2\text{—}1)$$

Let;

$$\left.\begin{aligned}\dot{\varphi}_{f1m}&=k_{f1m}\dot{i}_1\\ \dot{\varphi}_{f2m}&=k_{f2m}\dot{i}_2\\ \dot{\varphi}_{qm}&=k_m\dot{i}_q\\ \dot{\varphi}_{dm}&=k_{dm}\dot{i}_0\\ \dot{\varphi}_{cm}&=k_{cm}\dot{i}_c\\ \dot{\varphi}_{am}&=k_{am}\dot{i}_a\end{aligned}\right\} \qquad (2\text{—}2)$$

where $k_{f1m}, k_{f2m}, k_{qm}, k_{cm}$, and k_{am} are the proportional constants between the fluxes and the corresponding exciting current. It is noticeable that if the relation is not linear, these will be the non-linear function of the corresponding current.

The resultant direct-axis flux is, now, composed of;

$$\dot{\varphi}_f=k_{f1m}\dot{i}_1+k_{f2m}\dot{i}_2+k_{qm}\dot{i}_q+(k_{dm}+k_{cm})\dot{i}_0+k_{am}\dot{i}_a \qquad (2\text{—}3)$$

When the direct-axis component of the magnetic flux created by the quadrature winding current is negligible (practically the quadrature winding current contributes negligible effect onto the direct axis flux component), then the above relation reduces further into:

$$\dot{\varphi}_f=k_{f1m}\dot{i}_1+k_{f2m}\dot{i}_2+(k_{dm}+k_{cm})\dot{i}_0+k_{am}\dot{i}_a \qquad (2\text{—}4)$$

If the positive direction of the field flux is taken to the same direction with the flux by the field current i_1, then equation(2—3) and equation (2—4) are simplified in the following scalar form;

$$\varphi_f = k_{f1m}i_1 - k_{f2m}i_2 + (k_{cm} - k_{dm})i_0 - k_{am}i_a + k_{qm}i_q \quad (2\text{—}5)$$

or

$$\varphi_f = \varphi_{f1m} - \varphi_{f2m} + (\varphi_{cm} - \varphi_{dm}) - \varphi_{am} + \varphi_{qm} \quad (2-6)$$

and for equation (2—4);

$$\varphi_f = k_{f1m}i_1 - k_{f2m}i_2 + (k_{cm} - k_{dm})i_0 - k_{am}i_a \quad (2-7)$$

or

$$\varphi_f = \varphi_{f1m} - \varphi_{f2m} + (\varphi_{cm} - \varphi_{dm}) - \varphi_{am} \quad (2-8)$$

The quadrature-axis flux is composed of;

$$\dot{\varphi}_q = \dot{\varphi}_{f1q} + \dot{\varphi}_{f2q} + \dot{\varphi}_{qq} + \dot{\varphi}_{dq} + \dot{\varphi}_{cq} + \dot{\varphi}_{aq} \quad (2-9)$$

Let;

$$\left.\begin{aligned} \dot{\varphi}_{f1q} &= k_{f1q}\dot{i}_1 \\ \dot{\varphi}_{f2q} &= k_{f2q}\dot{i}_2 \\ \dot{\varphi}_{qq} &= k_{qq}\dot{i}_q \\ \dot{\varphi}_{dq} &= k_{dq}\dot{i}_0 \\ \dot{\varphi}_{cq} &= k_{cq}\dot{i}_c \\ \dot{\varphi}_{aq} &= k_{aq}\dot{i}_a \end{aligned}\right\} \quad (2-10)$$

$$\dot{\varphi}_q = k_{f1q}\dot{i}_1 + k_{f2q}\dot{i}_2 + k_{qq}\dot{i}_q + k_{dq}\dot{i}_o + k_{cq}\dot{i}_c + k_{aq}\dot{i}_a \quad (2\text{—}11)$$

When the main field current i_1, and i_2 and the auxiliary winding current i_a do not contribute any considerable effect onto the quadrature-axis flux component, then;

$$\dot{\varphi}_q = k_{qq}\dot{i}_q + k_{dq}\dot{i}_0 + k_{cq}\dot{i}_c \quad (2\text{—}12)$$

or

$$\dot{\varphi}_q = \dot{\varphi}_{qq} + \dot{\varphi}_{dq} + \dot{\varphi}_{cq} \quad (2\text{—}13)$$

In scalar notation;

$$\varphi_q = \varphi_{qq} + (\varphi_{cq} - \varphi_{dq}) \quad (2\text{—}14)$$

or

$$\varphi_q = k_{qq}i_q + k_{cq}i_c - k_{dq}i_0 \quad (2\text{—}15)$$

where $(k_{cq} - k_{dq})$ term is included to consider the secondary armature reaction effect.

3. Derivation of Machine Dynamics

Refering to figure 1, let R_1, R_2, R_c, R_a, and R_{de} denote the reluctances of the magnetic circuits for each of the corresponding flux; φ_{f1m}, φ_{f2m}, φ_{cm}, φ_{am}, and φ_{dm}, respectively and P_1, P_2, P_c, P_a, and P_{de} be the inverse of the corresponding reluctances of the magnetic pathes, thus;

$$\left.\begin{aligned} &\varphi_{f1m} = N_1i_1/R_1 = P_1N_1i_1 \\ &\varphi_{f2m}N_2i_2/R_2 = P_2N_2i_2 \\ &\varphi_{am} = N_ai_a/R_a = P_aN_ai_a \\ &\varphi_{cm} = N_ci_c/R_c = P_cN_ci_c \\ &\text{and} \\ &\varphi_{dm} = k_{de}N_di_0/R_{de} = P_{de}k_{de}N_di_0 \end{aligned}\right\} \quad (3\text{—}1)$$

For the control field circuit, the following loop relation can be written, neglecting the flux leakage between the windings;

$$R_1i_1 - R_2i_2 + N_1\frac{d\varphi_f}{dt} + N_2\frac{d\varphi_f}{dt} = e_{11} - e_{12} = e_1 \quad (3\text{—}2)$$

or substituting the obtained values for φ_f,

$$\begin{aligned} R_1i_1 - R_2i_2 &+ P_1N^2{}_1\frac{di_1}{dt} - P_2N_1N_2\frac{di_2}{dt} \\ &+ P_cN_1N_c\frac{di_c}{dt} - P_{de}k_{de}N_1N_d\frac{di_0}{dt} \\ &- P_aN_aN_1\frac{di_a}{dt} + P_1N_1N_2\frac{di_1}{dt} \\ &- P_2N_2{}^2\frac{di_2}{dt} + P_cN_2N_c\frac{di_c}{dt} \\ &- P_{de}k_{de}N_dN_2\frac{di_0}{dt} - P_aN_aN_2\frac{di_a}{dt} \\ &= e_{11} - e_{12} = e_1 \end{aligned} \quad (3\text{—}3)$$

Let:

$$\left.\begin{aligned} L_1 &= P_1N_1{}^2 \\ L_2 &= P_2N_2{}^2 \\ M_{12} &= P_2N_1N_2 \\ M_{21} &= P_1N_1N_2 \\ M_{a1} &= 2P_aN_aN_1 \\ M_{a2} &= 2P_aN_aN_2 \\ M_{c1} &= 2P_cN_cN_1 \\ M_{c2} &= 2P_cN_cN_2 \end{aligned}\right\} \quad (3\text{—}4)$$

Under the condition of the even-distribution of the control field winding, the compensating winding and the auxiliary winding along the stator cores, and, further, with the assumption of the symmetric construction of the machine, the magnetic reluctances of the corresponding pathes should have equal value, that is;

$$R_1 = R_2 = R_a = R_c \text{ or } P_1 = P_2 = P_c = P_a \quad (3\text{—}5)$$

Substituting these relations into equation (3—3), it yields;

$$\begin{aligned} R_1i_1 + L_1\frac{di_1}{dt} &- M_{12}\frac{di_2}{dt} - \frac{1}{2}M_{a1}\frac{di_a}{dt} \\ &+ \frac{1}{2}M_{c1}\frac{di_c}{dt} - P_{de}k_{de}N_dN_1\frac{di_0}{dt} \\ &- R_2i_2 - L_2\frac{di_2}{dt} + M_{21}\frac{di_1}{dt} - \frac{1}{2}M_{a2}\frac{di_a}{dt} \\ &+ \frac{1}{2}M_{c2}\frac{di_c}{dt} - P_{de}k_{de}N_dN_2\frac{di_0}{dt} \end{aligned}$$

$$=e_{11}-e_{12}=e_1 \quad (3-6)$$

Furthermore, for the balanced control winding, $R_1=R_2=R_f$ and $N_1=N_2=N_f$ and hence, $L_1=L_2=L_f$, $M_{12}=M_{21}=M_f$, $M_{a1}=M_{a2}=M_{af}$, and $M_{c1}=M_{c2}=M_{cf}$.

Now, equation (3—6) can be further simplified into;

$$R_f i_f+L_f\frac{di_f}{dt}+M_f\frac{di_f}{dt}-M_{af}\frac{di_a}{dt}+M_{cf}\frac{di_0}{dt}-M_{de}\frac{di_0}{dt}=e_1 \quad (3-7)$$

where $i_f=(i_1-i_2)$ is the effective control field current and $M_{de}=2P_{de}k_{de}N_dN_1=2P_{de}k_{de}N_dN_2$.

Let $\varphi_{eff}=\varphi_{f1m}-\varphi_{f2m}=N_f(i_1-i_2)/R_1=N_fi_f/R_1=P_fN_fi_f$ be the effective control field flux, then the virtual direct-axis conrtrol flux is expressib leas;

$$\varphi_f=\varphi_{f1m}-\varphi_{f2m}+\varphi_{cm}-\varphi_{dm}-\varphi_{am}=\varphi_{eff}+\varphi_{cm}-\varphi_{dm}-\varphi_{am} \quad (3-8)$$

Note that the quadrature component of the flux is composed of $\varphi_q=\varphi_{qq}+\varphi_{cq}-\varphi_{dq}$. Let $\boldsymbol{R}_q, \boldsymbol{R}_{cq}$, and $\boldsymbol{R}_{dq}$ denote the magnetic relutances along the quadrature-axis magnetic circuits for each of the flux components, $\varphi_{qq}, \varphi_{cq}$, and φ_{dq}, respectively, then;

$$\left.\begin{aligned}\varphi_{qq}&=N_qi_q/\boldsymbol{R}_q=P_qN_qi_q\\ \varphi_{cq}&=k_{cq}N_ci_c/\boldsymbol{R}_{cq}=P_{cq}k_{cq}N_ci_c\\ \varphi_{dq}&=k_{dq}N_di_0/\boldsymbol{R}_{dq}=P_{dq}k_{dq}N_di_0\end{aligned}\right\} \quad (3-9)$$

where k_{cq} and k_{dq} represent the effective fraction of the respective MMF in the quadrature-axis direction.

Assuming no operation of the quadrature field over to the region to yield the over-all magnetic saturation, the following loop equation for the quadrature winding circuit can be obtained;

$$R_qi_q+N_q\frac{d\varphi_q}{dt}=e_g=g_{fq}\cdot\varphi_f=g_{fq}\cdot\varphi_{eff}+g_{fq}\cdot\varphi_{cm}-g_{fq}\cdot\varphi_{de}-g_{fq}\cdot g_{am}=g_{fq}P_fN_fi_f+g_{fq}P_fN_ci_c-g_{fq}P_{de}k_{de}N_di_0-g_{fq}P_fN_ai_a \quad (3-10)$$

Let;

$$\left.\begin{aligned}L_q&=P_qN_q^2\\ M_{cq}&=P_{cq}N_qk_{cq}N_c\\ M_{dq}&=P_{dq}N_qk_{dq}N_d\\ K_{fq}&=g_{fq}P_fN_f\\ K_{dq}&=g_{fq}(P_fN_c-P_{de}k_{de}N_d)\\ &\text{and}\\ K_f&=g_{fq}P_fN_a\end{aligned}\right\} \quad (3-11)$$

In the above expression, g_{fq} is the transfer constant between the induced emf in the quadrature winding, e_g, and the direct axis field flux. It should be treated as a function of the main field flux when the machine is allowded to be over-driven into the saturable region

Substitution of the above relations into equation (3—10) yields the following loop equation, that is;

$$R_qi_q+P_qN_q^2\frac{di_q}{dt}+P_{cq}k_{cq}N_qN_c\frac{di_c}{dt}-P_{dq}k_{dq}N_qN_d\frac{di_0}{dt}=K_{fq}i_f+K_{dq}i_0-K_1i_a \quad (3-12)$$

Or in terms of inductances;

$$R_qi_q+L_q\frac{di_q}{dt}+M_{cq}\frac{di_c}{dt}-M_{dq}\frac{di_0}{dt}=K_{fq}i_f+K_{dq}i_0-K_fi_a \quad (3-13)$$

Finally, for the direct winding circuit, the loop equation yields the following voltage equilibrium relation;

$$R_d'i_0+R_ci_0-N_d\frac{d\varphi_f}{dt}+N_c\frac{d\varphi_f}{dt}=g_{qd}\cdot\phi_q-e_0 \quad (3-14)$$

Substituting equation (3—1), equation (3—8) and equation (3—9) into the above expression to have;

$$(R'_d+R_c)i_0-N_d\frac{d\varphi_{eff}}{dt}-N_d\frac{d\varphi_{cm}}{dt}+N_d\frac{d\varphi_{dm}}{dt}+N_d\frac{d\varphi_{am}}{dt}+N_c\frac{d\varphi_{eff}}{dt}+N_c\frac{d\varphi_{cm}}{dt}-N_c\frac{d\varphi_{dm}}{dt}-N_c\frac{d\varphi_{am}}{dt}=g_{qd}P_qN_qi_q+g_{qd}P_{cq}N_ci_c-g_{qd}P_{dq}k_{dq}N_di_0-e_0 \quad (3-15)$$

or

$$(R'_d+R_c)i_0-P_fN_dN_f\frac{di_f}{dt}-P_fN_dN_c\frac{di_0}{dt}+P_{de}k_{de}N_d^2\frac{di_0}{dt}+P_aN_aN_d\frac{di_a}{dt}+P_fN_cN_f\frac{di_f}{dt}+P_fN_c^2\frac{di_0}{dt}-P_{de}k_{de}N_cN_d\frac{di_0}{dt}-P_aN_aN_c\frac{di_a}{dt}=g_{qd}P_qN_qi_q+g_{qd}P_{cq}k_{cq}N_ci_c-g_{qd}P_{cq}k_{dq}N_di_0-e_0 \quad (3-16)$$

To simplify the above expression, let;

$$\begin{aligned}R_d&=R'_d+R_c\\ M_{fd}'&=P_fN_dN_f\\ M_{fc}'&=P_fN_cN_f\end{aligned}$$

$$\left.\begin{aligned}
&M_{fc}=M_{fc}'-M_{fd}'\\
&M_{ca}=M_{ac}'-M_{ad}'\\
&L_d=L_d'+L_c=P_{de}k_{de}N^2_d+P_fN^2_c\\
&M_{dc}=P_fN_dN_c+P_{de}k_{de}N_cN_d\\
&M_{ad}'=P_aN_aN_d\\
&M_{ac}'=P_aN_aN_c\\
&K_{qd}=g_{qd}P_qN_q\\
&K_{cq}=g_{qd}P_{cq}k_{cq}N_c\\
\text{and}\quad &K_{dd}=g_{qd}P_{cq}k_{dq}N_d
\end{aligned}\right\}\qquad(3\text{—}17)$$

Now, equation (3—18) is expressible in the following compact form;

$$R_di_0+M_{fc}\frac{di_f}{dt}+L_d\frac{di_0}{dt}-M_{ca}\frac{di_a}{dt}-M_{dc}\frac{di_0}{dt}=K_{qd}i_q+K_{cq}i_0-K_{dd}i_0-e_0\qquad(3\text{—}18)$$

4. State Representation of the Dynamic Characteristics

To obtain the adequate set of the state variables, the results thus far obtained in the proceeding discussions are tabulated below;

$$R_fi_f+L_f\frac{di_f}{dt}+M_f\frac{di_f}{dt}-M_{af}\frac{di_a}{dt}+M_{cf}\frac{di_0}{dt}-M_{de}\frac{di_0}{dt}=e_1$$

$$R_qi_q+L_q\frac{di_q}{dt}+M_{cq}\frac{di_c}{dt}-M_{dq}\frac{di_e}{dt}=K_{fq}i_q+K_{dq}i_0-K_fi_a\qquad(4\text{—}1)$$

and

$$R_di_0+M_{fc}\frac{di_q}{dt}+L_d\frac{di_0}{dt}-M_{ca}\frac{di_a}{dt}-M_{dc}\frac{di_0}{dt}=K_{qd}i_q+K_{cq}i_c-K_{dd}i_0-e_0$$

Let the load impedance be in the general form of $Z_L=(R_L+L_Ls)$, then;

$$e_0=R_Li_0+L_L\frac{di_0}{dt}\qquad(4\text{—}2)$$

From the dynamic equations and the load condition in the above, the transfer relations of the signals inside the machine are evaluated and they are displayed in figure 2, in the form of signal-flow graphs. The signal transitions at the steady state are also shown below, for later references.

$$\left.\begin{aligned}
&I_f=E_1/Z_f+Z_{af}I_a/Z_f-Z_{cdf}I_0/Z_f\\
&I_q=K_{fq}I_f/Z_q+K_{dq}I_0/Z_q-K_fI_a/Z_q-Z_{cdq}I_0/Z_q\\
&I_0=K_{qd}I_q/[Z_d+(K_{dd}-K_{cq})]\\
&\quad-E_0/[Z_d+(K_{dd}-K_{cq})]\\
&\quad-Z_{fc}I_f/[Z_d+(K_{dd}-K_{cq})]\\
&\quad+Z_{ca}I_a/[Z_d+K_{dd}-K_{cq})]
\end{aligned}\right\}\qquad(4\text{—}3)$$

and $E_0=Z_LI_0$

In the expression of the above, the impedance terms are abbreviated in the followings and the symbol,s, stands for the first derivative of the corresponding variable with respect to time.

$$\begin{aligned}
&Z_f=[R_f+(L_f+M_f)s]\\
&Z_q=(R_q+L_qs)\\
&Z_{cdf}=[(M_{cf}-M_{de})s]\\
&Z_{af}=[(M_{af})s]\\
&Z_{cdq}=[(M_{cq}-M_{dq})s]\\
&Z_d=[R_d+(L_d-M_{dc})s]\\
&Z_{fc}=[(M_{fc})s]\\
&Z_{ca}=[(M_{ca})s]\\
\text{and}\quad &Z_L=(R_L+L_Ls)
\end{aligned}$$

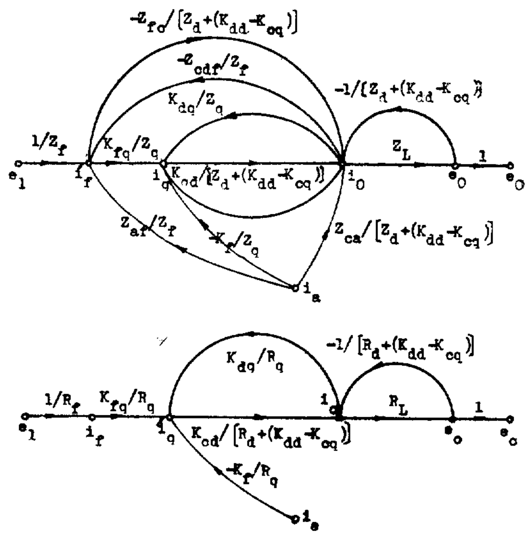

그림 2. 기계내부에서의 제어신호의 전달
Fig. 2. A signal flow graph for the machine,

Refering to figure 2, it is reasonable to select the state variables to be of i_f, i_q, and i_0. The control voltage e_1 and the current in the auxiliary winding circuit are taken to form the control vector to investigate the compensating effect onto the machine dynamics, for the later work.

This results to the following sets of the state equations;

$$\frac{di_f}{dt}=\frac{-R_f}{(L_f+M_f)}i_f+\frac{(M_{de}-M_{cf})}{(L_f+M_f)}\frac{di_0}{dt}$$

$$+\frac{1}{(L_f+M_f)}e_1+\frac{M_{af}}{(L_f+M_f)}\frac{di_a}{dt}$$

$$\frac{di_q}{dt}=\frac{K_{fq}}{L_q}i_f-\frac{R_q}{L_q}i_q+\frac{[K_{dq}+(M_{dq}-M_{cq})d/dt]}{L_q}i_0-\frac{K_f}{L_q}i_a$$

$$\frac{di_0}{dt}=\frac{-M_{fc}}{(L_0-M_{dc})}\frac{di_f}{dt}+\frac{K_{qd}}{(L_0-M_{dc})}i_q+\frac{[(K_{cq}-K_{dd})-(R_d+R_L)]}{(L_0-M_{dc})}i_0+\frac{M_{ca}}{(L_0-M_{dc})}\frac{di_a}{dt} \qquad (4-4)$$

where $L_0=(L_d+L_L)$, $R_{dc}=(R_d-K_{cq}+K_{dd})$

$R_0=(R_d+R_L)$

or, in matrix notation, the state eqation becomes to;

$$\begin{pmatrix}\frac{di_f}{dt}\\ \frac{di_q}{dt}\\ \frac{di_0}{dt}\end{pmatrix}=\begin{pmatrix}\frac{-R_f}{(L_f+M_f)} & 0 & \frac{(M_{de}-M_{cf})}{(L_f+M_f)}\frac{d}{dt}\\ \frac{K_{fq}}{L_q} & \frac{-R_q}{L_q} & \frac{[K_{dq}+(M_{dq}-M_{cq})d/dt]}{L_q}\\ \frac{-M_{fc}}{(L_0-M_{dc})}\frac{d}{dt} & \frac{K_{qd}}{(L_0-M_{dc})} & \frac{-(R_L+R_{dc})}{(L_0-M_{dc})}\end{pmatrix}\begin{pmatrix}i_f\\ i_q\\ i_0\end{pmatrix}+\begin{pmatrix}\frac{1}{(L_f+M_f)} & \frac{M_{af}}{(L_f+M_f)}\frac{d}{dt}\\ 0 & \frac{-K_f}{L_q}\\ 0 & \frac{M_{ca}}{(L_0-M_{dc})}\frac{d}{dt}\end{pmatrix}\begin{pmatrix}e_1\\ i_a\end{pmatrix} \qquad (4-5)$$

and the output equation is:

$$e_0=Z_Li_0 \qquad (4-6)$$

It may be interestiong, at this point, to investigate the conditions for the complete compensation of the machine operation from the armature reaction effect.

For the proper compensation from the demagnetization effect, the resultant effective flux components in the direction of both of the direct-axis and the quadrature axis should satisty the following relation, so that both of the control winding and the quadrature winding circuit are completely decoupled from influences due to the load current, i_0, that is;

$$\varphi_{cm}=\varphi_{dm} \text{ and } \varphi_{cq}=\varphi_{dq} \qquad (4-7)$$

then, equation (3—8) and equation (3—9) are reduced to;

$$\varphi_f=\varphi_{eff}-\varphi_{am},\ \varphi_q=\varphi_{qq} \qquad (4-8)$$

These require the following conditions for the complete decoupling from the demagnetization effect,

$$k_{de}=N_c/N_d \text{ and } k_{dq}=k_{cq}\ N_c/N_d \qquad (4-9)$$

so that $M_{cf}=M_{de}$, $M_{cq}=M_{dq}$, and $K_{dq}=0$ should hold.

Under these proper-compensation conditions, the dynamic equation of the machine is obtainable from equation (3—7), equation (3—14), and equation (3—17) and the results are tabulated below (assumed $P_{cq}=P_{dq}$, and $P_f=P_{de}$);

$$\left.\begin{aligned}&R_fi_f+L_f\frac{di_f}{dt}+M_f\frac{di_f}{dt}-M_{af}\frac{di_a}{dt}=e_1\\ &R_qi_q+L_q\frac{di_q}{dt}=K_{fq}i_f-K_fi_a\\ &R_di_0+M_{fc}\frac{di_f}{dt}-M_{ca}\frac{di_a}{dt}\\ &\quad=K_{qd}i_q+(K_{cq}-K_{dd})i_0-e_0\end{aligned}\right\}$$

and

$$e_0=Z_Li_0 \qquad (4-10)$$

The signal flow graph for the properly compensated case is shown in figure 3. The lower graph shows the signal transitions inside the machine at a steady-state operation.

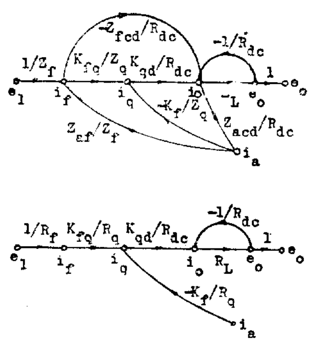

그림 3. 減磁作用이 적절히 보상되었을때의 기계내부에서의 제어신호의 전달.

Fig 3. A signal flow under the properly compensated case from the demagnetization effect.

In the figure, the machine parameters are abbreviated in the form of impedances, that is;

$$\left.\begin{aligned} &Z_f=[R_f+(L_f+M_f)s] \\ &Z_q=(R_q+L_q s) \\ &Z_{af}=(M_{af}s) \\ &Z_{fcd}=[(M'_{fc}-M'_{fd})s] \\ &Z_{acd}=[(M'_{ac}-M'_{ad})s] \\ &R_{dc}=(R_d-K_{cq}+K_{dd}) \\ \text{and}\quad &Z_L=(R_L+L_L s) \end{aligned}\right\} \qquad (4\text{—}11)$$

The state model for this case can be deduced in the following matrix form;

$$\begin{pmatrix} \frac{di_f}{dt} \\ \frac{di_q}{dt} \\ \frac{di_0}{dt} \end{pmatrix} = \begin{pmatrix} \frac{-R_f}{(L_f+M_f)} & 0 & 0 \\ \frac{K_{fq}}{L_q} & \frac{-R_a}{L_q} & 0 \\ -M_{fc}\frac{d}{dt} & \frac{K_{qd}}{L_L} & \frac{-(R_L+R_{dc})}{L_L} \end{pmatrix} \begin{pmatrix} i_f \\ i_q \\ i_0 \end{pmatrix} + \begin{pmatrix} \frac{1}{(L_f+M_f)} & \frac{M_{af}}{(L_f+M_f)}\frac{d}{dt} \\ 0 & -K_f/L_q \\ 0 & M_{ca}\frac{d}{dt}/L_L \end{pmatrix} \begin{pmatrix} e_1 \\ i_a \end{pmatrix} \qquad (4\text{—}12)$$

And, for the output equation;

$$e_0=Z_L i_0$$

It may be worthwhile to mention the machine dynamics under no-load condition. The signal flow for the unloaded machine is shown in figure 4. The lower graph is for the steady-state operation of the machine under the corresponding load condition.

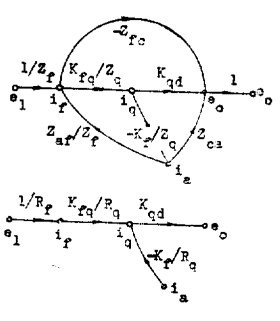

그림 4. 무부하시의 기계내부에서의 제어신호의 전달
Fig 4. Signal flow under no-load condition

The state model for this case becomes in the following form;

$$\begin{pmatrix} \frac{di_f}{dt} \\ \frac{di_q}{dt} \end{pmatrix} = \begin{pmatrix} \frac{-R_f}{(L_f+M_f)} & 0 \\ \frac{K_{fq}}{L_q} & \frac{-R_q}{L_q} \end{pmatrix} \begin{pmatrix} i_f \\ i_q \end{pmatrix} + \begin{pmatrix} \frac{1}{(L_f+M_f)} & \frac{-M_{af}}{(L_f+M_f)}\frac{d}{dt} \\ 0 & \frac{-K_f}{L_q} \end{pmatrix} \begin{pmatrix} e_1 \\ i_a \end{pmatrix} \qquad (4\text{—}13)$$

and the output equation becomes;

$$e_0=-M_{fc}\frac{di_f}{dt}+k_{qd}i_q+M_{ca}\frac{di_a}{dt} \qquad (4\text{—}14)$$

Conclusions and Discussions

1. The state-variable representation of tha amplidyne generator with the balanced control winding and with the auxiliary feedback winding reveals that it's dynamics can be formulated in the three-dimensional coordinates system, as shown in equation (4—5) and equation (4—15). The three variables, i_f, i_q, and i_0 can be an adequate set of the state variables for the machine.
2. When the proper compensation from the demagnetization is achieved so that $M_{cf}=M_{de}$, $M_{cq}=M_{dq}$, and $K_{dq}=0$, then the machine dynamics is further simplified as obtained in equation (4—15). This requires that $k_{de}=N_c/N_d$, $k_{dq}=k_{eq}N_c/N_d$ should hold.
3. Signal flow graphs shown in figure 2, in figure 3, and in figure 4 show distinguishable picture of the internal transitions of signals inside the machine. If the magnetic couplings of the feedback compensating winding to the other field-windings contribute so insignificant effect that the mutual inductances, M_{fa} and M_{ca} can be neglected, then, the effect by the feedback current, i_a is pronouncedly accentuated in the resulting flow graphs from which adequate feedback compensation schemes can be depicted.
4. Even under the linearized condition of the state model, the coefficient matrix of the machine dynamics is time-variant. When the non-linearities are taken into account in the

analysis, the machine parameters are the nonlinear function of the other state variables and certain elements in the coefficient matrix turn to be nonlinear and time-variant.

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