論 文
28—6—2

電力系統 周波數의 最適制御에 關한 研究

Optimal Control of Power System Frequency

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Abstract

This paper describes a new systematic and straightforward method for constructing an optimal observer system for the optimal load frequency controller. The method is based on the iterative minimization of the newly defined performance measure in regard to the estimate error of the reduced order Luenberger observer system which identifies unmeasurable states and system disturbances, and uses the previous results of the author's paper already published such as the optimal load frequency control policy, exponential disturbance model, etc..

The procedure employing the method is illustrated with a simplified two-area load-frequency system example which can be interpreted as being a generalization of any multi-area system. The results demonstrate the remarkable advantages and feasibility of the method presented herein.

I. INTRODUCTION

Load-frequency control(LFC) in electric power systems has gained in importance with the growth of interconnected systems. Particularly, the requirements for constant frequency, economic dispatch control and security control schemes demand the LFC system as a prerequisite.

Conventional LFC is mainly based on tie-line bias control where each area tends to reduce area control error(ACE):

$$\mathrm{ACE}=\Delta P_{\mathrm{tie}}+k_1\Delta f \tag{1}$$

and the control law m is determined by the proportional integral:

$$m(t)=k_2\cdot \mathrm{ACE}+k_3\int_0^t \mathrm{ACE}\cdot dt \tag{2}$$

where Δf and ΔP_{tie} are, respectively, the requency deviation from the desired value and the tie line power deviation from the predetermined value and parameters k_1, k_2 and k_3 are determined empirically or intuitively. With the development of modern control theory, new concepts have been introduced for the design of the optimal LFC system and they have involved the use of more exact mathematic models and the applications of optimal control theory, currently receiving increasing attention.

The basic LFC system dynamics is nonlinear, but are usually approximated by the linear state equation:

$$\dot{x}=Ax+Bm+Dp \tag{3}$$

$$y=Cx \tag{4}$$

where $x(t)$, $m(t)$, $p(t)$ and $y(t)$ are, respectively $n\times 1$ state, $r\times 1$ control, $q\times 1$ disturbance (load disturbance), and $y\times 1$ output (measurable state) vectors, and A, B, C and D are matrices of appropriate dimensions.

The performance measure J_1 for Eqs. 1 and 2 could be taken to have the quadratic form:

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接受日字 : 1979年 4月 25日

$$J_1=\frac{1}{2}\int_0^\infty[(x-x_f)'Q(x-x_f)+(m-m_f)'R(m-m^f)]dt \quad (5)$$

if p is a known constant vector, and accordingly $x^f \triangleq x|_{t\to\infty}$ and $m_f \triangleq m|_{t\to\infty}$ are known a priori, where Q and R are, respectively, $n\times n$ and $r\times r$ positive definite constant matrices. Then, the feedback gains of interest are the ones which rlesut from the minimization of J_1 in Eq 5.

Despite years of theoretical research on the linear quadratic design methology, the LFC system requirements still suffer from the following problems

i) Identification of unmeasurable states:

For most cases in real LFC system, only partial information (y) of the system states such as frequency deviation, tie-line power deviation, etc. is available for measurement, and so the feedback gains for optimal control need to extract or identify the unmeasurable states by some proper means.

ii) Identification of load disturbances:

Like above, information of load disturbances (p) is also unmeasurable and unpredictable, presenting the same problem as above.

iii) Unknown x_f and m_f:

The performance measure(J_1) in Eq. 5 can be minimized on the assumptions that p remain constant within the time period considered and that x_f and m_f accordingly be known apriori. But neither is p constant, nor x_f and m_f known in advance.

iv) Smoothness of control actious:

The first derivative of control vector(dm/dt) is regarded as a criterion for control action smoothness. One of the LFC system requirements is to maintain smooth control signals for the reasons of preventing the governor demages, securing economic and reliable unit operations, etc.. But J_1 in Eq. 5 does not reflect this constraint.

v) Local availability of state and disturbance information:

A multi-area or multi-pool system actually adopts the decentralized or hierarchical LFC system and so it is unrealistic for a local system to utilize information of other areas' states and disturbances within reach of its own area, even though available for measurement.

The first work based on modern control theory in this field was done by Fosha and Elgerd [2], assuming that the entire states be completely available for measurement and that disturbances be known a priori. Therefore, it is apparent that the control is not feasible for the reasons cited above.

Cavine et al. [3], introducing a modified Kalman filter, performed the load disturbance identification, but the approach has distinct shortcomings by assuming that the tie-line power deviation be known and also that statistical noise data be available.

Miniesy and Bohn [4] suggested the use of a Luenberger observer to identify unmeasurable states and disturbances, but their work needs further improvements, since the disturbances, represented by step functions are poorly modelled by simply setting their first derivatives to zero.

The author's former work [1] suggested an iternative method for constructing the optimal LFC system, which achieved some improvements in the derivation of the optimal control law and the identification of unmeasurable states and disturbances. The concepts presented herein was based on a new disturbance model represented by a sequence of exponential functions and on the same Luenberger observer as above for the identification. But the work was confined to a single area problem, and the parameter determination in conjunction with constructing the observer system resorted intuitively to trial -and-error method.

It is, therefore, the aim of this paper to extend the former work to a multi-area LFC problem, and to construct the observer system optimally according to a newly defined performance index rather than relying on the trial-and-error method. In addition, the method suggested herein may be useful answers to the aforesaid problems except v) which is beyond the scope of this paper.

Ⅱ. EXPONENTIAL DISTURBANCE MODEL AND OBSERVER

For the direct use of the former work [1] done by the author in later sections this section briefely cites its main results.

i) Exponential disturbance model:

So far as the load disturbance model suggested by Miniesy and Bohn is concerned, each element of the disturbance vector p is represented by a succession of step changes. This is not, however, very satisfactory, since differentiation of p then gives rise to impulse functions. This difficulty is overcome in the former treatment by representing p by exponential approximation in the manner indicated in Fig. 1 and as describe by Eq. 6.

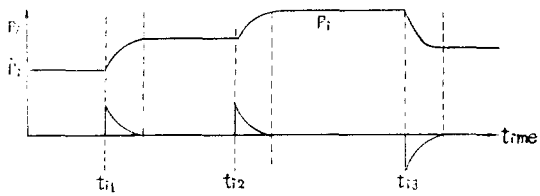


Fig. 1. Disturbance and its derivative.

$$p\triangleq[p_1 p_2 \cdots\cdots p_q]' \tag{6}$$

$$\dot{p}\triangleq[\dot{p}_1 \dot{p}_2 \cdots\cdots \dot{p}_q]' \tag{7}$$

$$\ddot{p}\triangleq[\ddot{p}_1 \ddot{p}_2 \cdots\cdots \ddot{p}_q]'=-\alpha\dot{p}+\alpha r \tag{8}$$

where,

$$p\triangleq\sum_j k_{ij}\left\{1-\exp\{-\alpha)t-t_{ij})\}\right\}u(t-t_{ij}) \tag{9}$$

$$\dot{p}_i=\alpha\sum_j k_{ij}\exp\{-\alpha(t-t_{ij})\}u(t-t_{ij}) \tag{10}$$

$$\ddot{p}_i=-\alpha\dot{p}_i+\alpha\sum_j k_{ij}\delta(t-t_{ij}) \tag{11}$$

$$r\triangleq[r_1 r_2 \cdots\cdots r_q]^t$$

$$r_i\triangleq\sum_j k_{ij}\delta(t-t_{ij})$$

$u(t), \delta(t)$: unit step and impulse functions, respectively

t_{ij} : the j-th arival time of the i-th disturbance

α : arbitrarily selected positive number sufficiently large.

The inclusion of p and $\dot{p}$ in the x leads to the augmented states $\hat{x}=[x' \vdots p' \vdots \dot{p}']'$, and accordingly, Eqs. 3 and 4 are also augmented as

$$\dot{\hat{x}}=\hat{A}\hat{x}+\hat{B}m+\alpha Vr \tag{14}$$

$$y=\hat{C}\hat{x} \tag{15}$$

where

$$\hat{A}\triangleq\begin{pmatrix} \overset{n}{A} & \vdots \overset{q}{D} & \vdots \overset{q}{O_1} \\ O_1' & \vdots O_2 & \vdots I_1 \\ O_1' & \vdots O_2 & \vdots -\alpha I_1 \end{pmatrix}\begin{matrix} n \\ q \\ q \end{matrix}=\begin{pmatrix} \overset{q}{\hat{A}_{11}} & \vdots \overset{n+2q-g}{\hat{A}_{12}} \\ \hat{A}_{21} & \vdots A_{22} \end{pmatrix}\begin{matrix} g \\ n+2q-g \end{matrix} \tag{16}$$

$$\hat{B}\triangleq\begin{pmatrix} \overset{r}{B} \\ O_3 \\ O_3 \end{pmatrix}\begin{matrix} n \\ q \\ q \end{matrix}=\begin{pmatrix} B_1 \\ B_2 \\ O_3 \\ O_3 \end{pmatrix}\begin{matrix} g \\ n-g \\ q \\ q \end{matrix}=\begin{pmatrix} \overset{r}{B_1} \\ \hat{B}_2 \end{pmatrix}\begin{matrix} q \\ n+2q-g \end{matrix} \tag{17}$$

$$\hat{C}\triangleq[\overset{n}{C} \vdots \overset{q}{O_4} \vdots \overset{q}{O_4}]g=[\overset{q}{I_2} \vdots \overset{n-g}{O_5} \vdots \overset{q}{O_4} \vdots \overset{q}{O_4}]g$$

$$=[\overset{g}{I_2} \vdots \overset{n+2q-g}{O_6}]g \tag{18}$$

$$V\triangleq\begin{pmatrix} \overset{q}{O_7} \\ I_1 \end{pmatrix}\begin{matrix} n+q \\ q \end{matrix}=\begin{pmatrix} \overset{q}{O_4} \\ V_1 \end{pmatrix}\begin{matrix} g \\ n+2q-g \end{matrix} \tag{19}$$

I_i, O_i : identity and null matrices with approriate dimensions

ii) Optimal control with all measurable states and known disturbances:

Assuming that the entire system states x and disturbance p be completely available for measurement and p remain constant to infinite time and also that the LFC system be asymptotically stable and completely controllable, even though actually not feasible, it can be shown that there exist E and S such that

$$x_f\ Ep_f \tag{20}$$

$$m_f=Sp_f \tag{21}$$

where E, S : $n\times q$ and $r\times q$ constant matrices, respectively and the optimal control vector $\overset{*}{m}$, which minimizes J_1 in Eq. 5 by solving a steady state Riccati equation, is given by

$$\overset{*}{m}=Hx+(S-HE)p_f\approx Hx+(S-HE)p \tag{22}$$

where H : $r\times n$ constant gain matrix

$$p_f\triangleq p|_{t\to\infty}$$

It is noted that in Eq. 22 p_f is inevitably replaced by the present, p, since future information of p is unpredictable.

iii) Observer system and identification:

For identifying unmeasurable state x_u and disturbances p, the augmented states $\hat{x}$ is futher partitioned as

$$\hat{x}\triangleq[y' \vdots x_u' \vdots p' \vdots \dot{p}']' \tag{23}$$

where x_u : $(n-g)\times 1$ unmeasurable states

Assuming that the LFC system be observable, the reduced order Luenburger observer system [5] is expressed as

$$\dot{\bar{z}}=F\bar{z}+Gy+Mm+\alpha V_1 r \qquad (24)$$

$$\bar{z}=\bar{w}-Ly \qquad (25)$$

where

$F\triangleq\hat{A}_{22}-L\hat{A}_{12}$, $G\triangleq(\hat{A}_{22}-L\hat{A}_{12})L+\hat{A}_{21}-LA_{11}$

$M\triangleq\hat{B}_2-LB_1$

L : $(n+2q-g)\times g$ constant matrix to be arbitrarily selected

$\bar{w}\triangleq[\bar{w}'_u \vdots \bar{w}_p' \vdots \dot{\bar{w}}_p']'$: unmeasurable state, disturbance and disturbance derirative estimate vectors to be identified

However, neglecting the fourth unmeasurable term $\alpha V_1 r$ in Eq. 24, Eqs. 24 and 25 are approximated by

$$\dot{z}=Fz+Gy+Mm \qquad (26)$$

$$z=w-Ly=w-[\overset{n-g}{L_u'} \vdots \overset{q}{L_p'} \vdots \overset{q}{L_{\dot{p}}'}]'y \qquad (27)$$

where $w\triangleq[w_u' \vdots w_p' \vdots w'_{\dot{p}}]'$: approximate $\bar{w}$

It can be shown that the error contribution Δw $(=\bar{w}'-w)$ is negligible if the observer system in Eq. 24 is asymptotically stable [1]. Therefore, the unmeasurable x_u and p are reasonably identified by the relations:

$$x_u\approx w_u\approx\bar{w}_u \qquad (28)$$

$$p\approx w_p\approx\bar{w}_p \qquad (29)$$

Consequently, the optimal oontrol $\hat{m}$ can be implemented with the use of the obesrver system (Eqs. 26 and 27) and Eq. 22 as

$$\hat{m}=H_1 y+H_2 w_u+(S-HE)w_p \qquad (30)$$

where $H\triangleq[H_1,\ H_2]$ and the structure of the composite plant and controller is illustrated in Fig. 2.

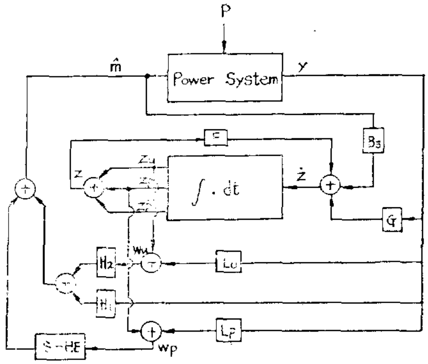


Fig. 2. Power system with a load-frequency controller.

III. OPTIMAL OBSERVER SYSTEM

It is the primary concern of this paper to formulate an optimal$(n+2q-g)$th- order observer from the $(n+2q)$th LFC system by choosing a matrix L in Eq. 27 such that it achieves desired (optimal) response characteristics of the observer. The observer response time chosen should be fast enough to provide convergence of the estimates within the time interval of interest.

In a deterministic system, it has, however, been not clearly defined up to now on a quantitative basis, what the observer is optimal or what the fast response time means, while in stochastic cases the observer system design has been shown to be optimized in the presence of measurement noise in a sense of minimizing the mean square estimation error.

In the former cases, the conventional way of designing the observer system is to choose arbitrarily any desired set of $(n+2q-g)$ eigenvalues of F in Eq. 26 or its equavalents in a sense of a sympotical stability in try-and error approaches.

So far as the deterministic observer system is concerned, the following difficulties bother the system designer:

1) The desired set of F's eigenvalues is not clear in a quantitative sense.

2) Even though the desired set is chosen, the corresponding matrix F or$L$ is not unique and so the determination of L resorts to try-and-error approaches.

3) It is probable that the matrix L thus determined is subject to hardware limitations, say, $L_{min}\leq L\leq L_{max}$, in the case of actual implementation of physical system.

The concept to be present herein, as a possible answer to that, will define a new performance measure for the deterministic observer system, and then suggest the procedures for constructing the optimal observer system on the defined basis.

That is, Eq. 26 can be solved for z from Eqs. 14 and 26 as

$$z=[x_u', p', \dot{p}']'-Ly+\exp\{(\hat{A}_{22}-L\hat{A}_{12})t\}\cdot(z_0-[x'_{u0}, p_0', \dot{p}_0']'+Ly_0) \qquad (31)$$

where $z_0 \triangleq z|_{t=0}$, $y_0 \triangleq y|_{t=0}$, $x_{u0} \triangleq x_u|_{t=0}$ $p_0 \triangleq p|_{t\to\infty}$, $\dot{p}_0 = \dot{p}|_{t\to\infty}$ And, accordingly, the estimate error vector of unmeasurable states and disturbances, $\varepsilon(=[x_u' p' \dot{p}'] - \omega)$, from Eq. 27 and 31, results in

$$\varepsilon = \exp\{(\hat{A}_{22} - L\hat{A}_{12})t\}\varepsilon_0 \tag{32}$$

where $\varepsilon_0 \triangleq \varepsilon|_{t=0}$

The performance measure J_2 for the observer system to be minimized for L is defined by

$$J_2(L) \triangleq \frac{1}{2}\int_0^\infty \varepsilon'\varepsilon dt = \frac{1}{2}\varepsilon_0'\int_0^\infty \exp\{(\hat{A}_{22} - L\hat{A}_{12})t\}\exp\{(\hat{A}_{22} - L\hat{A}_{12})t\}dt\varepsilon \tag{33}$$

$$\text{subject to } L_{min} \leq L \leq L_{max} \tag{34}$$

where each element of L_{max} and L_{min} is, respectively, the prescribed upper and lower limit of the corresponding element of L.

In order to use the performance measure J_2Eq. 33 for the case of unknown initial states it is usually necessary to eliminate this dependence on ε_0. A simple way for this is to average the performance obtained for a linearly independent set of initial states.

Therefore, assuming the initial states ε_0 to be random variables uniformly distributed on the surface of the n-dimensional unit sphere, Then, the expected value $\overline{J}_2$ is

$$\overline{J}_2(L) = \frac{1}{2n}\int_0^\infty tr[\exp\{(\hat{A}_{22} - L\hat{A}_{12})'t\}\exp\{(\hat{A}_{22} - L\hat{A}_{12})t\}]dt \tag{35}$$

and $n\overline{J}_2$ is an upper bound on the worst case performance obtained in the case that $\varepsilon_0'\varepsilon = 1$, since it is apparant for an arbitrary matrix A and an arbitrary vector x with the condition $x'x = 1$ that

$$\max_x (A\varepsilon)' \leq tr(A'A) \tag{36}$$

For this reason, the performance measure J_3 used hereafter is defined by

$$J_3(L) \triangleq \int_0^\infty tr[\exp\{(\hat{A}_{22} - L\hat{A}_{12})'t\}\exp\{(\hat{A}_{22} - L\hat{A}_{12})t\}]dt = trQ(L) \tag{37}$$

subject to $L_{min} \leq L < L_{max}$

Consequently, next task is to construct the optimal observer system such that

$$\overset{*}{J}_3 = \min_L J_3(L) = J_3(L^*) \tag{38}$$

The optimal values of parameters L will be found numerically by the well-behaved computational procedures described below rather than by analitical approaches.

The procedures consist of two computational a lgorithms. the procedures consist of two computational algorithms.

The first algorithm may be powerful for finding the rough values of L^*, while the second one is used for more accurate determination of L^*.

A. The first stage of computation of L^*

Considering Eq. 37, the assumption of the asymptotical decaying behavior of $\exp\{(\hat{A}_{22} - L\hat{A}_{12})t\}$ makes it possible to approximate the infinite time interval of integration by some definite time τ properly choosen, and also due to the convergence characteristics of J_3 for L the high-order terms in the elements of L higher than the second order could be truncated in each element of L. The approximated J_3 thus formed is defined by J_4. That is,

$$J_3(L) \approx J_4(L, \tau) \tag{39}$$

subject to $L_{min} \leq L \leq L_{max}$

Then, instead of minimizing $J_2(L)$, $J_4(L, \tau)$ are minimized for L and τ but the optimality is evaluated by $J_3(L)$. It is noted that too large scalar value of τ causes $J_4(L, \tau)$ to deviate far from $J_3(L)$ since $J_4(L, \tau)$'s highest order terms are the second order and accordinly $J_4(L, \tau)$ is unbound as $\tau \to \infty$, and contrarily too small τ means to cover the only small portion of the integral area resulting in the same situation as the former cases. Therefore, it is apparent that there exist the optimal τ^* such that

$$\min_\tau |J_3(L^*) - J_4(L^*, \tau)| = |J_3(L^*) - J_4(L^*, \tau^*)| \tag{40}$$

For a given τ, $J_4(L, \tau)$ is quadratic in L and the necessary condition for minimizing $J_4(L, \tau)$ for L is the following linear equation:

$$\frac{\partial J_4(L, \tau)}{\partial L} = 0 \tag{41}$$

The solution L of Eq. 41 is L_τ as the guess of L^* in this iteration. Then, its optimality is evaluated by substituting L_τ in to J_3.

Before substitution, L_τ should be checked for constrains in Eq. 34, and in the case of being outside the admissible ranges modified by fixing L_τ to the limit values, L_{max} or L_{min}.

The actual value of J_3 in Eq. 37 is obtained from the solution of the following linear equation:

$$(\hat{A}_{22}-L_\tau\hat{A}_{12})'Q+Q(\hat{A}_{22}-L_\tau\hat{A}_{12})+J=0 \quad (42)$$

and by

$$J_3(L_\tau)=trQ \quad (43)$$

Then, in order to improve J_3, the present τ is changed properly. For changes of τ it is very efficient to employ the symmetrical two-point search method [7] which is applicable to one-directional search problem.

The iterative scheme is summarized as below:

i) Guess initial τ^i. i : terative count

ii) Solve L_{τ^i} from Eq. 41, and modify $L_\tau{}^i$ by the constraint check in Eq. 34, if necessary. If all the element of L_{τ^i} are constrained, go to vi) other wise, go to iii).

iii) Solve Q^i from Eq. 42, and evaluate $J_3(L_\tau{}^i)$ from. Eq. 43.

iv) Test $|J_3(L_{\tau^i})-J_3(L_\tau{}^{i-1})|\leq$error limit
True : Go to vi). False : Go to V)

v) Change τ^i to τ^{i+1} by the STPSM. and increase i to $i+1$. then go to ii).

vi) If the optimal values thus obtained are met for practical use, terminate the iteration. If more accurate results are needed, proceed with the second stage of computation bescribed below.

It is noted that for $F\triangleq\hat{A}_{22}-L\hat{A}_{12}$ in Eq. 25, the structural sparsity of $\hat{A}_{22}$ makes F to be irrelevant of some portions of L's elements, and such elements vanishing are set to arbitrary values.

B. The second stage of computation L^*.

The first computational scheme is very powerful to get the approximate L^*, but it has the obvious shortcomings that the exact optimal values are never reached due to its inherent approximation algorithm.

For more accurate L^*, it is suggested to use the following gradient method which may attain theoretically the exact optimums with infinite number of iteration.

In the gradient method, the improved L^{i+1} is determined by

$$L^{i+1}=L^i-\rho\cdot\frac{\partial J_3(L)}{\partial L}\Big|_{L=L^i} \quad (44)$$

where ρ : calculating step size(scalor)

i : iteration count

and then L^{i+1} is modified by the constraints in Eq. 34.

The procedures for the evaluation of $J_3(L^{i+1})$ and its convergence test are the same as in the first stage of computation.

For deriving the fomula for $\partial J_3(L)/\partial L$, a Kleiman's lemma [6] is useful and, therefore, quoted as

"Let $f(x)$ be a trace function. Then if one can write $f(x+\epsilon\Delta x)-f(x)=\epsilon tr[M(x)\cdot\Delta x]$ (45) as $\epsilon\to0$, where $M(x)$ is an $n\times r$ matrix and x is an $r\times n$ matrix, then

$$\frac{\partial f(x)}{\partial x}=M'(x) \quad (46)$$

$f(\cdot)$ is a trace function of the matrix x if $f(x)$ is of the form

$$f(x)=tr[F(x)]\text{"} \quad (47)$$

and another useful formula for this purpose can be found and cited as [6]

$$\exp\{(A-FC-\epsilon\Delta FC)t\}=\exp\{(A-FC)t\}-\epsilon\int_0^\infty\exp\{A-FC)(t-\sigma)\Delta FC\cdot\exp\{(A-FC)\sigma\}d\sigma \quad (48)$$

With the use of the Kleiman's lemma and Eq. 48, $\partial J_3(L)/\partial L$ can be derived as

$$\frac{\partial J_3(L)}{\partial L}=-\int_0^\infty\exp\{(\hat{A}_{22}-L\hat{A}_{12})'t\}\cdot\exp\{\hat{A}_{22}-L\hat{A}_{12})t\}dt\cdot\int_0^\infty\exp\{(\hat{A}_{22}-L\hat{A}_{12})t\}\cdot\exp\{(\hat{A}_{22}-L\hat{A}_{12})'t\}dt\cdot A'_{12}=-Q_1\cdot Q_2\cdot A'_{12} \quad (49)$$

where Q_1 and Q_2, respectively, are the solution of the following linear equations:

$$(\hat{A}_{22}-L\hat{A}_{12})'Q_1+Q_1(\hat{A}_{22}-L\hat{A}_{12})+I=0 \quad (50)$$

$$(\hat{A}_{22}-L\hat{A}_{12})Q_2+Q_2(\hat{A}_{22}-L\hat{A}_{12})'+I=0 \quad (51)$$

Consequently, the iterative scheme is summarized as below:

i) Take initial L^i from the result of the first stage above

ii) Eq. 51 is solved for Q_2^i. Q_1^i has been already calculated at the preceding time of iteration.

iii) Calculate $\partial J_3(L)/\partial L|L=L^i$ from Eq. 49.

iv) Calculate L^{i+1} from Eq. 45.

v) Modify L^{i+1} by the constraint check in Eq. 34, if necessary. If all the elements of L^{i+1} are constrained, go to viii) Otherwise, go to vi).

vi) Solve $Q_1{}^{i+1}$ from Eq. 50 and then evaluate $J_3(L^{i+1})$ from Eq. 43.

vii) Test $|J_3(L^{i+1})-J_3(L^i)|\leq$ error limit

True : Go to viii). False : Increase i to $i+1$ and go to ii)

viii) Terminate the iteration.

Ⅲ. EXAMPLE

The presented method is tested on a simplified two area power system.

The augmented state vector $\hat{x}$ consisting of measurable 3 states, unmeasurable 4 states, unmeasurable 2 disturbance and 2 first-denratives of the disturbances are as follows:

$$\hat{x}=\begin{pmatrix} y \\ \hdashline x_u \\ \hdashline p \\ \hdashline \dot{p} \end{pmatrix}=\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ \hdashline x_4 \\ x_5 \\ x_6 \\ x_7 \\ \hdashline p_1 \\ p_2 \\ \hdashline \dot{p}_1 \\ \dot{p}_2 \end{pmatrix}=\begin{pmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta p_{tie} \\ \hdashline \Delta x_{e1} \\ \Delta p_{g1} \\ \Delta x_{e2} \\ \Delta p_{g2} \\ \hdashline \Delta p_{d1} \\ \Delta p_{d2} \\ \hdashline \Delta \dot{p}_{d1} \\ \Delta \dot{p}_{d2} \end{pmatrix}$$

$$=\begin{pmatrix} \text{area-1 frequency deviation} \\ \text{area-2 frequency deviation} \\ \text{tie-line power deviation} \\ \hdashline \text{governor-1 position} \\ \text{generator-1 output change} \\ \text{governor-2 position} \\ \text{generator-2 output change} \\ \hdashline \text{area-1 load disturbance} \\ \text{area-2 load disturbance} \\ \hdashline \text{area-1 disturbance derivative} \\ \text{area-2 disturbance derivative} \end{pmatrix}$$

and the control vector m is $m=[m_1, m_2]'$. The observer system matrix $F(=\hat{A}_{22}-L\hat{A}_{12})$ and L are, respectively, of the structure;

$$F=\begin{pmatrix} a, & el_{11}, & 0, & fl_{12}, & 0, & -fl_{12}, & 0 \\ c, & c+el_{21}, & 0, & fl_{22}, & 0, & -fl_{22}, & 0 \\ 0, & el_{31}, & b, & fl_{32}, & 0, & -fl_{32}, & 0 \\ 0, & el_{41}, & d, & d+fl_{42}, & 0, & -fl_{42}, & 0 \\ 0, & el_{51}, & 0, & fl_{52}, & 1, & -fl_{52}, & 0 \\ 0, & el_{61}, & 0, & fl_{62}, & -d, & -fl_{62}, & 0 \\ 0, & el_{71}, & 0, & fl_{72}, & 0, & -fl_{72}, & 1 \\ 0, & el_{81}, & 0, & fl_{82}, & 0, & -fl_{82}, & -\alpha \end{pmatrix}$$

$$L'=\begin{pmatrix} l_{11}, & l_{21}, & l_{31}, & l_{41}, & l_{51}, & l_{61}, & l_{71}, & l_{81} \\ l_{12}, & l_{22}, & l_{32}, & l_{42}, & l_{52}, & l_{62}, & l_{72}, & l_{82} \\ l_{13}, & l_{23}, & l_{33}, & l_{43}, & l_{53}, & l_{63}, & l_{73}, & l_{83} \end{pmatrix}$$

In this example, two cases of load disturbance are assumed as

$$\text{case A}:\begin{cases} p_1=\Delta p_{d1}=0.1\sin(2\pi t/10)+0.05\sin(2\pi\times 9t/10)+0.02\sin(2\pi\times 81t/10) \\ p_2=\Delta p_{d2}=0, \text{ for all } t \end{cases}$$

$$\text{case B}:\begin{cases} p_1=\begin{cases} =0.01, & 0\leq t<2.5 \\ =0.1, & 2.5\leq t<5 \\ =0, & 5\leq t \end{cases} \\ p_2=0, \text{ for all } t \end{cases}$$

At first, computations were done for Eq. 22 in either disturbance cases without the observer, assuming that all the states and disturbance be available for feedback information to the input controller. and then, next comtations were for Eq. 30 which corresponds to the optimal LFC with the optimal observer system suggested herein. How the suggested method is an efficient one is shown in Figs. 3~6 below which compare both results. Fig. 3 and 4 demonstrate the observer system's performances. The computed results for actual (p_1) and estimated (w_{p1}) load disturbances and actual (ΔP_{g1}) and estimated (W_{P1}) power changes are compared in Figs. 3 and 4, respectively.

On the other hand, one could make a judgement on the suggested method's applicability by reviewing Figs. 5 and 6, since Fig. 5 compares the optimally controlled frequency deviations for Eq. 22's and Eq. 30's scheme, and Fig. 6 compares the optimal control signals for both scheme. In Fig. 3 and 4, the real line and dotted line represent real and estimated values, respectively, while in Figs. 5 and 6, the former those for Eq. 22 and the latter those for Eq. 30.

The comparisons for the results are summarized as

i) The observer system errors were very small in a sense of its practical opplicability.

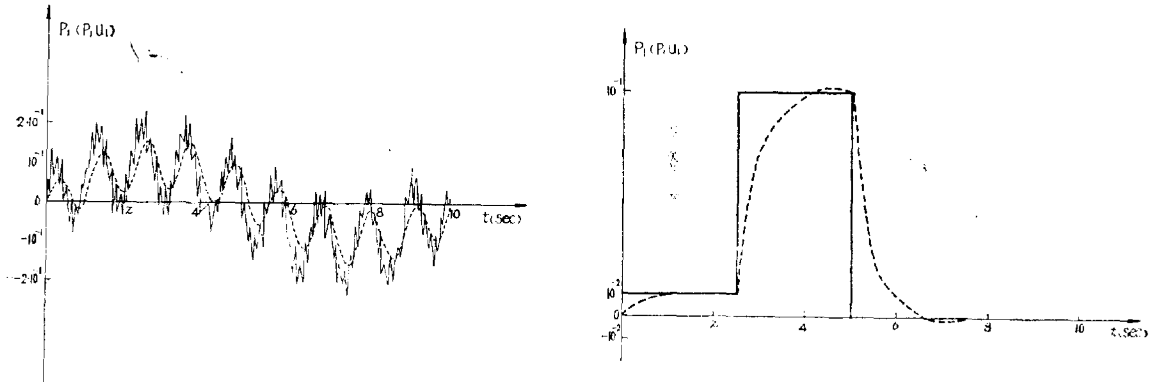
ii) Unmeasurable states and disturbances were smoothed due to the filtering characteristics of the observer system and it was accordingly possible to maintain smooth control octions favorable for the LFC requirements.

iii) The overall performance measure J defined by Eq. 5 was not so much increased with the use of the observer system(12% for case A and 7% for case B), and the observer error J_2 defined by Eq. 33, was increased to 7% for case B.

Ⅳ. CONCLUSTIONS

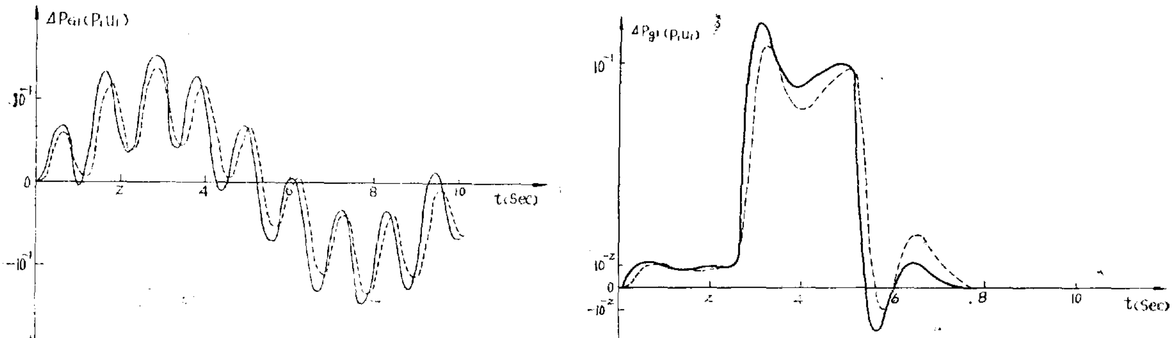
The main conclusions of this paper are summarized as

i) The exponential disturbance model developed in the former work by the author with the aid



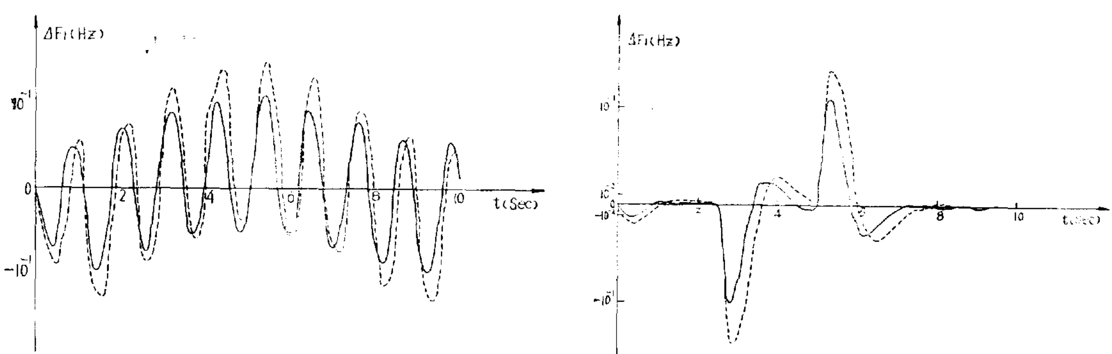
case A case B

Fig. 3. Real and estimated disturbances.



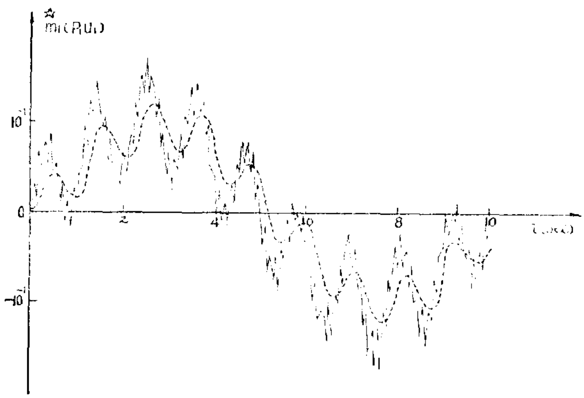
case A case B

Fig. 4. Real and estimated generating power changes.

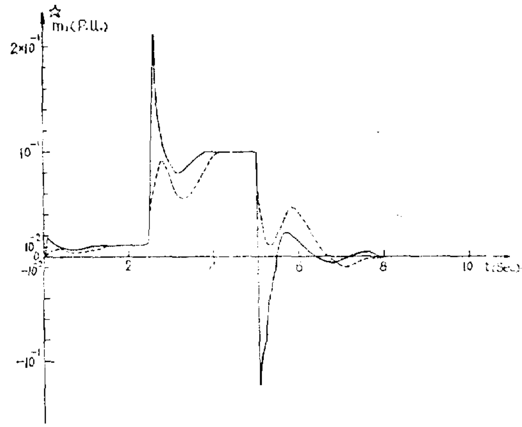


case A case B

Fig. 5. Frequency deviation by the optimal control with all states and disturbances measurable and with observer information.



case A



case B

Fig. 6. Optimal control signal with all states and disturbances measurable and with observer information.

of the optimal observer suggested here in demonstrated its efficient performances in the LFC system

ii) The optimal observer system for the LFC was mathematically defined in terms of its performance measure newly defined herein.

iii) Efficient algorithms were derived for constructing the optimal observer system.

iv) Smooth frequency control actions were realized by the method presented here in.

ACKNOWLEDGMENT

The author acknowledges the financial assistance provided by the Korea Science and Engineering Foundation in the pursuance of this work.

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