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TWO-AREA ANALYSIS OF SYSTEM TIME DEVIATION AND INADVERTENT INTERCHANGE ENERGY ACCUMULATION IN INTERCONNECTED POWER SYSTEMS

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I. INTRODUCTION

A. Tie-line Bias Control

The net interchange tie-line bias control has been the accepted operating practice in the United States and Canadian interconnected power systems for about forty years [1]. This technique has been an important factor in the extensive growth of interconnected power systems.

A large interconnected power network is made up of many control areas. Each control area has a controller that depends for operation on a signal called the area control error (ACE). The ACE of an area is the sum of two local signals [2]. One is the deviation of the net power flows (in MW) on all the tie-lines connecting the control area to its neighbors, from the scheduled net power flows (in MW). The other is the frequency bias power, which is the product of a factor called frequency bias setting (in MW/Hz) times the frequency deviation from schedule (in Hz).

Each area controller is expected to adjust the area generation automatically to make its ACE zero. When the system frequency is on schedule, the frequency bias power of each area is zero. Each area is expected to maintain the net power flow on the tie-lines to its neighbors on schedule and thereby absorb its own load variations. Thus, each area has the regulating responsibility for absorbing its own load changes, as well as for helping to maintain the system frequency on schedule.

If, however, one or more areas are not fulfilling their own responsibility, the system frequency is off schedule. The scheduled net power flows of other areas are adjusted by their own frequency bias power. Other areas are expected to maintain their own net tie-line power flows on the adjusted schedule and thereby assist the deficient areas and help restore the system frequency. This cooperative assistance between areas is one of the planned benefits of the tie-line bias control of an interconnected system [3].

B. Statement of Problem

Recently, objectionable fluctuations in the system frequency and large flows of the so-called "inadvertent interchange energy" have been experienced in the interconnected system of North America [1]. The term "inadvertent interchange energy" (in MWH) is the time integral of the deviation of the area net tie-line power flows from its schedule. The power systems that are part of the Western Systems Coordinating Council (WSCC) are also experiencing the accumulation of an excessive amount of inadvertent interchange energy between control areas. These occurrences suggest that present-day overall regulation is less effective than it was in the past. There has been growing interest in analyzing the area control performance, to understand the causes of accumulation of inadvertent interchange energy, and to stimulate the appropriate corrective control actions.

Nathan Cohn [3] recently introduced the idea of decomposition of the so-called "system time deviation" and inadvertent interchange energy. The term "system time deviation" (in seconds) is the time integral of the deviation of the system frequency from schedule. The system time deviation can be decomposed into Q area components where Q is the number of control areas in the interconnection. The inadvertent interchange energy of an area can be decomposed into Q area components: a "primary component" caused by the area itself, and (Q-1) "secondary components" caused by each of the other areas in the interconnection. Cohn also suggested that these decomposed components can be used in control performance evaluation [4]. The analysis presented in this dissertation is based on the concepts developed by Cohn.

C. Scope of Research

The approach proposed in this dissertation differs from Cohn's approach in one respect. Instead of analyzing (Q-1) secondary components, they are lumped into one, i.e., the sum of the contributions caused by all the other areas in the interconnection. Thus, for any one control area, the other control areas in the interconnection are considered as one equivalent area. The system time deviation and the inadvertent interchange energy are considered as two coordinates of a vector. A 2x2 matrix equation is derived that relates the area components of the system time deviation of two equivalent areas with the system time deviation and the area inadvertent interchange energy. This matrix equation can be graphically illustrated on a two-dimensional Cartesian plane. The properties of the decomposed components on this Cartesian plane are investigated.

The two-area analysis is used to review various corrective control schemes. Among the schemes to be studied are: the present corrective control schemes of the National Electric Reliability Council - Operating Committee (NERC-OC) [5,6] on the system time deviation and the inadvertent interchange energy, and the so-called "synchronized, coordinated correction scheme" suggested by Cohn [7]. These schemes are compared in terms of energy (MWH) needed for correction.

The causes of accumulation of the inadvertent interchange energy are explored. Computer results are shown and analyzed for a variety of conditions that can lead to the increase of the inadvertent interchange energy in the area of concern. A six-area test system is used for this purpose. Computer results for demonstrating the effects of the decomposed components are shown and analyzed.

A debit/credit system based on Q area components of system time deviation is suggested. There are many ways to define the debit/credit system. Three examples of the debit/credit system are presented and compared with the system suggested by Nathan Cohn [4].

II. REVIEW OF LITERATURE

A. Frequency Bias Setting

The net tie-line bias control has been developed in North America since the 1940s and is mainly attributed to Nathan Cohn [8,9]. He explored the relationship of the frequency bias setting to natural frequency governing characteristics of a control area [10,11]. A bias setting that is higher than the natural frequency governing characteristic of the area has been used in practice. If the system frequency is off schedule because one or more areas are not fulfilling their own regulating responsibility, the remaining areas in the interconnection assist these areas, i.e., they adjust their respective generation by an amount greater than the required by their own governing action (governor and load governing), and thus help restore the system frequency quickly.

Elgerd and Fosha [12] questioned the whole control strategy in this technique, using optimal control theory and applying it to a two-area interconnection. They also developed a state variable model of load frequency control problems of multiarea electric energy systems [13]. Their results suggested that better response and wider stability margins can be obtained by lower bias settings. In the discussion of their papers, Cohn reminded that bias settings of about the half of natural frequency governing characteristics were actually standard practice prior to the presentation in 1956 in one of his papers [10]. He pointed out that it hardly seems desirable to return to a practice found to be objectionable in actual operation and has since been discarded. He also pointed out that their results are valid only if the step-load change can be accommodated in the area in which it occurred. If this step-load change cannot be accommodated in the area in which it occurred, other areas should provide assistance to the area in need for the full duration of the need and this cooperative assistance between areas is one of the benefits of interconnected operation. Later, Willems [14] showed that no convincing argument supports the recommendations of Elgerd and Fosha to use lower bias settings through sensitivity analysis of the optimum performance of load frequency control.

The actual natural frequency governing characteristic of a control area is not a linear function of the frequency deviation. Because of governor deadband and insensitivity to small frequency deviations, it is a nonlinear function. The question of the bias magnitude and several related aspects still remain an area for research [1].

B. Short-term Swings and Trends

Tie-line power flows, system frequency and area control error based on measurements of these parameters have a continually varying nature. However, the technique "net tie-line bias control" is based on quasi-steady-state analysis. Supplementary control seeks to maintain the "steady-state" values of these parameters, and no effort is made to regulate for their short-term swings. The modern Automatic Generation Control (AGC) system has a sophisticated digital filter so as to refine its ACE and eliminate or compensate for the short period swings and to not permit such short-term swings to initiate control action [15]. Based on this filtered ACE signal, a raise or lower signal is sent to the appropriate generating units that are assigned the task of regulating while fulfilling objectives of economy, security and environmental dispatch.

Ross [16] suggested use of the error adaptive control computer (EACC) that monitors the control error signal and makes logical decisions on how much, if any, control action should be taken depending on the chracteristics of the error signal. Control action may be reduced to any judiciously chosen minimum by adjusting the EACC to discriminate against certain classes of disturbance, e.g., statistical, deterministic, and periodic. Fast control action may still be taken for large and/or sustained disturbances.

C. Application of Modern Control Theory

In the last decade, numerous papers have appeared in the technical literature attempting to apply modern control theory to the load frequency control problem and to apply digital control techniques.

Taylor and Cresap [17] used a digital simulation program for the design of an improved AGC control algorithm. These models include nonlinear digital filtering, digital power plant controllers, and stochastic load changes. Glover and Schweppe [18] suggested a discrete time, linear-plus-deadband control law. They investigated the problem of designing a load frequency control law that reduces transient frequency oscillations and reduces the number of control signals sent to power plants. Calovic [19] suggested a proportional-plus-integral optimal regulator solution of load frequency control based on a linear regulator design. The results indicate that substantial improvement can be achieved and a practical realization of this optimal approach would only require the extension of existing conventional systems by state proportional feedback, provided that the cost of the required additional telemeterings is solved adequately. Kwatny, Kalnitsky and Bhatt [20] suggested that load frequency control problem should be viewed as a "tracking" problem rather than as a "regulator" problem. Taking this point of view, a procedure was presented for the design of supplementary controls. The control system includes estimation and prediction of load as a primary function. These estimates and predictions are used to coordinate generation in each area so as to regulate power flows and frequencies.

It is interesting to note that the above approaches focus on the dynamic behavior of the system, while the aspects of the system performance that are considered to have been degraded pertain to quasi-steady-state behavior, namely, the sustained frequency drift and inadvertent interchange in the interconnected system. This view is substantiated by Bose and Atiyyah in Reference 21, in which regulation error in load frequency control of a power system is discussed. They suggested that good control of a power system is more dependent upon system constraints and human decisions than on the design of the present-day load frequency controller.

D. Corrective Control

At times, a control area may fail to regulate effectively either by not maintaining its scheduled net interchange when the system frequency is normal, or by not providing programmed frequency-bias assistance, because of one or more of the following reasons [3]:

(a) Errors in the measurements of frequency or net interchange power,

(b) Errors or offsets in the setting of frequency or net interchange schedules,

(c) Inadequacies in the control system, or its telemetering or communication channels, and

(d) Nonavailability or nonassignment of responsive generating units to generation control function.

These conditions in an area, including schedule offsets for corrective control, are identified as "area regulating deficiencies" [3]. The system time deviation and the inadvertent interchange energy accumulation are caused by regulating deficiencies of areas in the interconnection.

Mollman and Kennedy [22] discussed the interrelationship of the system time deviation, frequency deviation, and the net tie-line power deviation as it affects each system of the interconnection and the interconnection as a whole. Usry [23] pointed out that the inadvertent interchange energy cannot be completely eliminated, and that after-the-fact balancing is necessary. The corrective control schemes for the system time deviation and for the inadvertent interchange energy have been studied and are mainly attributed to Cohn [7,24]. He showed the effects of the offset terms in the ACE equation on all the control areas [24].

The operating manual of the Operating Committee of NERC gives the guidelines for correction of system time deviation and inadvertent energy accumulation to member utilities in the North American Interconnection. Guide No. 4 of the operating manual defines the time deviation correction scheme [5]. All areas are expected to simultaneously offset their frequency schedule by an amount related to accumulated system time deviation during the common time interval. Guide No. 5 of the manual defines the bilateral and unilateral correction schemes of the inadvertent interchange energy [6].

(a) The bilateral correction scheme is that an area with inadvertent interchange in one direction arranges correction with another area having inadvertent interchange in the opposite direction. Both areas should offset their interchange schedules simultaneously by the same amount, but of opposite sign. The system frequency is not affected.

(b) The unilateral correction scheme is that an area can shift the net interchange schedule to correct for its inadvertent interchange accumulation, provided that this control action is in a direction to correct the prevailing time deviation from schedule.

E. Recent Work on Corrective Control

Recently, many papers have appeared in the technical literature on energy balancing and time deviation correction. In 1976, Cohn [7] proposed the system-wide synchronized correction scheme. This scheme is based on the concept that inadvertent interchanges and time deviation accumulations result from common causes, and consequently they should be corrected by common control action. Their correction should not be regarded as two separate functions.

This system-wide synchronized correction scheme combines the system-wide inadvertent interchange correction and the system-wide time deviation correction schemes. All the control areas are required to participate in the scheme. According to this scheme, an area offsets its net interchange schedule by an amount proportional to its own inadvertent interchange accumulation. All areas have a common frequency offset proportional to system time deviation.

To validate this scheme, the authors of References 25 and 26 conducted a computer simulation study of a three-area test system. Both inadvertent interchange energy and system time error are corrected successfully in a common time interval, when this correction scheme is used.

1. The concept of decomposition

Cohn introduced the concept of decomposition of the system time deviation and the inadvertent interchange energy [3]. In an interconnected system made up of Q control areas, the following components are present:

(a) System time deviation can be decomposed into Q components. Each component is caused by the regulating deficiencies of a specific area. It is a measure (in seconds) of the control performance of that area.

(b) Inadvertent interchange energy of an area can be decomposed into Q components. A primary component is caused by the regulating deficiencies of the area itself. This primary component is a measure (in MWH) of the control performance of that area. Each of (Q-1) secondary components is caused by the regulating deficiencies in one of the other areas.

Cohn also pointed out the deficiencies of the present corrective techniques used by NERC as follows [4]:

(a) For the system time correction period, each area whose time deviation component has the same sign as the system time deviation will correct its own component (of system time deviation). However, each area whose time deviation component has a sign opposite to that of the system time deviation will increase its own component (of system time deviation).

(b) For the bilateral inadvertent interchange energy correction period, an area whose primary component of inadvertent energy has the same sign as that of its own inadvertent energy will correct its primary component. An area whose primary component of inadvertent energy has a sign opposite to that of its own inadvertent energy will increase its primary component.

Referring to the above problems, Cohn suggested an alternative technique that would replace the present two-step correction scheme [4]. The proposed technique is based on the concept of decomposition. This technique corrects simultaneously, by a single correction action, the area component of the system time deviation, the area primary component, and the secondary components of inadvertent interchange energy it has created in all other areas. This technique can be utilized unilaterally in an area regardless of whether the other areas are concurrently engaged in corrective control action.

The uniqueness of components of the system time deviation and area inadvertent interchange energy was proven by Zaborsky [27]. If there are Q control areas in the interconnection, there are Q area control errors, and Q net tie-line power deviations from their respective schedule and the common frequency deviation Δf.

He derived the QxQ matrix equation representing a linear transformation that maps Q-dimensional space (Q ACES) to Q-dimensional space ((Q-1) net tie-line power deviations and Δf). He showed that the QxQ matrix is nonsingular and, hence, the mapping is one-to-one.

III. TWO-AREA ANALYSIS

A. The Matrix Equation

For any control area, all other areas of the interconnection are considered as one equivalent area. Thus, the interconnected system is treated as a two-area system. Two equivalent areas are considered as a pair. If there are Q control areas in the interconnection, there are Q such combinations or pairs. The subscript i refers to signals associated with area i, while the subscript r refers to signals associated with the rest of the interconnection. It is to be understood that r is area-dependent, i.e., r(i). However, only the subscript r will be used for convenience.

Assuming that all area controllers are operating in the "net tie-line bias control" mode, the basic equation for the ACE of an area is given by [11]

$$ACE = \Delta T - 10B \cdot \Delta f \tag{3.1}$$

When the control signal for corrective control is added, and the measurement errors (as well as offset terms) are included, the resulting two-area basic equations are:

$$ACE_i + \tau_i - 10B_i\phi_i + (CORR)_i = \Delta T_i - 10B_i\ \Delta f \tag{3.2a}$$

$$ACE_r + \tau_r - 10B_r\phi_r + (CORR)_r = \Delta T_r - 10B_r\ \Delta f \tag{3.2b}$$

where

ACE_i is the area control error in MW of area i;

ΔT_i is $(T_i - T_{oi})$ where T_i is the actual area i net interchange in MW (power exported is treated as positive) and T_{oi} is the scheduled area i net interchange in MW;

Δf is $(F-F_o)$ where F is the system frequency in Hz and F_o is the scheduled system frequency in Hz;

B_i is the area i frequency bias setting in MW/.1 Hz and has a negative sign;

τ_i is $(\tau_{oi}-\tau_{1i})$ where τ_{oi} is an error in the setting of T_{oi} and τ_{1i} is an error in the measurement of T_i at area i;

ϕ_i is $(\phi_{oi}-\phi_{1i})$ where ϕ_{oi} is an error in the setting of F_o and ϕ_{1i} is an error in the measurement of F at area i;

$(CORR)_i$ is the offset term of area i for corrective control.

Similar terms apply to area r. These are given by:

$$ACE_r = \sum_{\substack{j=1 \\ j \neq i}}^{Q} ACE_j \qquad (3.3a)$$

$$\tau_r = \sum_{\substack{j=1 \\ j \neq i}}^{Q} \tau_j \qquad (3.3b)$$

$$\phi_r = \sum_{\substack{j=1 \\ j \neq i}}^{Q} \frac{B_j}{B_r} \phi_j \qquad (3.3c)$$

$$\Delta T_r = \sum_{\substack{j=1 \\ j \neq i}}^{Q} \Delta T_j \qquad (3.3d)$$

$$B_r = \sum_{\substack{j=1 \\ j \neq i}}^{Q} B_j \qquad (3.3e)$$

$$(CORR)_r = \sum_{\substack{j=1 \\ j \neq i}}^{Q} (CORR)_j \qquad (3.3f)$$

$$B_s = \sum_{j=1}^{Q} B_j \tag{3.3g}$$

The left-hand side terms of Eqs. 3.2a and 3.2b are defined as "regulating deficiencies" of areas i and r, respectively.

Integrating Eqs. 3.2a and 3.2b over a given time interval $[t_1, t_2]$ in hours,

$$\int_{t_1}^{t_2} (ACE_i + \tau_i - 10B_i\phi_i)dt + \int_{t_1}^{t_2} (CORR)_i\, dt = \int_{t_1}^{t_2} \Delta T_i\, dt - 10B_i \int_{t_1}^{t_2} \Delta f\, dt \tag{3.4a}$$

$$\int_{t_1}^{t_2} (ACE_r + \tau_r - 10B_r\phi_r)\, dt + \int_{t_1}^{t_2} (CORR)_r\, dt = \int_{t_1}^{t_2} \Delta T_r\, dt - 10B_r \int_{t_1}^{t_2} \Delta f\, dt \tag{3.4b}$$

By definition,

$$\sum_{j=1}^{Q} T_j = 0$$

$$\sum_{j=1}^{Q} T_{oj} = 0$$

and F and F_o are common to all areas. The scheduled frequency F_o is set at 60 Hz.

The increment of the system time deviation $\Delta\varepsilon$ (seconds) for the same interval is defined as

$$\Delta\varepsilon = 60 \int_{t_1}^{t_2} (F-60)\, dt \tag{3.5}$$

The increments of the inadvertent interchanges of areas i and r are defined as

$$\Delta I_i = \int_{t_1}^{t_2} (T_i - T_{oi}) dt \tag{3.6a}$$

$$\Delta I_r = \int_{t_1}^{t_2} (T_r - T_{or}) dt \tag{3.6b}$$

Then, from the definitions, $\Delta I_r = -\Delta I_i$.

Equation 3.4 can be written as a 2x2 matrix equation,

$$\begin{bmatrix} \int_{t_1}^{t_2} (ACE_i + \tau_i - 10B_i\phi_i)dt + \int_{t_1}^{t_2} (CORR)_i dt \\ \int_{t_1}^{t_2} (ACE_r + \tau_r - 10B_r\phi_r)dt + \int_{t_1}^{t_2} (CORR)_r dt \end{bmatrix} = \begin{bmatrix} \frac{-B_i}{6} & 1 \\ \frac{-B_r}{6} & -1 \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} \tag{3.7}$$

Rearranging Eq. 3.7, we get

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = (-\frac{6}{B_s}) \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \int_{t_1}^{t_2} (ACE_i + \tau_i - 10B_i\phi_i)dt + \int_{t_1}^{t_2} (CORR)_i dt \\ \int_{t_1}^{t_2} (ACE_r + \tau_r - 10B_r\phi_r)dt + \int_{t_1}^{t_2} (CORR)_r dt \end{bmatrix} \tag{3.8}$$

1. Definitions

(a) The time integral term, $[\int_{t_1}^{t_2} (ACE_i + \tau_i - 10B_i\phi_i)dt + \int_{t_1}^{t_2} (CORR)_i dt]$ in MWH is defined as "accumulated regulating deficiencies" of area i for the time interval. Similarly, $[\int_{t_1}^{t_2} (ACE_r + \tau_r - 10B_r\phi_r)dt + \int_{t_1}^{t_2} (CORR)_r dt]$ in MWH is the accumulated regulating deficiencies of area r.

(b) Components of the time deviation are defined as follows:

$$\Delta\varepsilon_{ig} = (-\frac{6}{B_s}) \int_{t_1}^{t_2} (ACE_i + \tau_i - 10B_i\phi_i)dt \tag{3.9a}$$

$$\Delta\varepsilon_{ic} = (-\frac{6}{B_s}) \int_{t_1}^{t_2} (CORR)_i dt \tag{3.9b}$$

$$\Delta\varepsilon_{rg} = (-\frac{6}{B_s}) \int_{t_1}^{t_2} (ACE_r + \tau_r - 10B_r\phi_r)dt \tag{3.9c}$$

$$\Delta\varepsilon_{rc} = (-\frac{6}{B_s}) \int_{t_1}^{t_2} (CORR)_r dt \tag{3.9d}$$

$$\Delta\varepsilon_i = \Delta\varepsilon_{ig} + \Delta\varepsilon_{ic} \tag{3.9e}$$

$$\Delta\varepsilon_r = \Delta\varepsilon_{rg} + \Delta\varepsilon_{rc} \tag{3.9f}$$

All the terms are in seconds because the time integral terms in MWH are multiplied by the common factor, $(-\frac{6}{B_s})$. B_s is the total bias setting of the system. $\Delta\varepsilon_i$ and $\Delta\varepsilon_r$ are defined as the accumulated regulating deficiencies in seconds of areas i and r, respectively. $\Delta\varepsilon_{ig}$

and $\Delta\varepsilon_{rg}$ are the accumulated regulating deficiencies in seconds caused by AGC control action in areas i and r, respectively. $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ are the accumulated regulating deficiencies in seconds caused by the corrective controls in areas i and r, respectively.

Equation 3.8 can be written as

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_i \\ \Delta\varepsilon_r \end{bmatrix} \tag{3.10}$$

The 2x2 matrix Eq. 3.10 represents two simultaneous equations with two unknowns. Because the 2x2 matrix is nonsingular for any area i, there exists a unique solution $(\Delta\varepsilon_i, \Delta\varepsilon_r)$ for a given set of $(\Delta\varepsilon, \Delta I_i)$.

Then, at $t = t_2$,

$$\begin{bmatrix} \varepsilon(t_2) \\ I_i(t_2) \end{bmatrix} = \begin{bmatrix} \varepsilon(t_1) \\ I_i(t_1) \end{bmatrix} + \begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} \tag{3.11a}$$

$$= \begin{bmatrix} \varepsilon(t_1) \\ I_i(t_1) \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ -\frac{B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_i \\ \Delta\varepsilon_r \end{bmatrix} \tag{3.11b}$$

$$= \begin{bmatrix} \varepsilon(t_1) \\ I_i(t_1) \end{bmatrix} + \begin{bmatrix} 1 \\ -\frac{B_r}{6} \end{bmatrix} \cdot (\Delta\varepsilon_{ig} + \Delta\varepsilon_{ic}) + \begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (\Delta\varepsilon_{rg} + \Delta\varepsilon_{rc}) \tag{3.11c}$$

The system time deviation and the inadvertent interchange energy of area i are considered as two coordinates of a vector. As shown in Eq. 3.11c, the final vector at $t = t_2$ is the vector sum of three vectors:

(a) the initial vector at $t = t_1$;

(b) the vector due to $\Delta\varepsilon_{ig}$ or $\Delta\varepsilon_{ic}$, and

(c) the vector due to $\Delta\varepsilon_{rg}$ or $\Delta\varepsilon_{rc}$.

Let the initial vector at t = $-\infty$ be zero. $\Delta\varepsilon_i$ and $\Delta\varepsilon_r$ during the time interval $(-\infty, t)$ are denoted as ε_i and ε_r, respectively. Then, at any time t,

$$\begin{bmatrix} \varepsilon \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \varepsilon_i \\ \varepsilon_r \end{bmatrix} \tag{3.12}$$

B. Graphical Decomposition

Equations 3.11 or 3.12 can be illustrated on a two-dimensional Cartesian plane. This Cartesian plane is defined as the (ε, I_i) plane. Its abscissa is the system time deviation in seconds and the ordinate is the inadvertent interchange energy of area i in MWH.

The operating point (ε, I_i) at any time t is represented as a vector $\overrightarrow{OP}$ from the origin to itself (Fig. 3.1). This vector $\overrightarrow{OP}$ is a linear combination of two basis vectors. While many different sets of basis vectors are possible, only three sets of basis vectors are considered.

1. The vector $\overrightarrow{OP}$ is a sum of the vectors $\overrightarrow{OA}$ and $\overrightarrow{OB}$ on Fig. 3.1.

$$\begin{bmatrix} \varepsilon \\ I_i \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot (\varepsilon) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot (I_i) = \overrightarrow{OA} + \overrightarrow{OB} \tag{3.13}$$

2. The vector $\overrightarrow{OP}$ is also a sum of the vectors $\overrightarrow{OC}$ and $\overrightarrow{OD}$ in Fig. 3.1.

From Eq. 3.12,

$$\begin{bmatrix} \varepsilon \\ I_i \end{bmatrix} = \begin{bmatrix} 1 \\ \frac{-B_r}{6} \end{bmatrix} \cdot (\varepsilon_i) + \begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (\varepsilon_r) = \overrightarrow{OC} + \overrightarrow{OD}$$

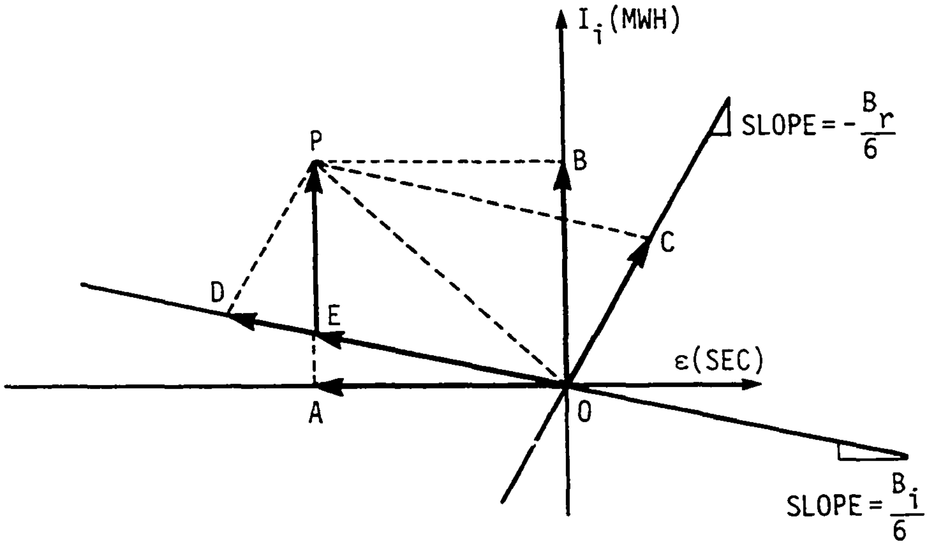


Figure 3.1. Graphical decomposition

$$= \begin{bmatrix} \varepsilon_i \\ I_{ii} \end{bmatrix} + \begin{bmatrix} \varepsilon_r \\ I_{ir} \end{bmatrix} \quad (3.14)$$

The vector $\vec{OC}$ is caused by the accumulated regulating deficiencies in area i and is not affected by those in area r. It also represents the area component of the system time deviation and the primary component of the inadvertent interchange. These are the same as the components defined by Cohn [3]. The accumulated regulating deficiencies in seconds is the area component of the system time deviation.

The vector $\vec{OD}$ is caused by the accumulated regulating deficiencies in area r and is not affected by those in area i. It also represents the area component of the system time deviation of area r and the secondary component of the inadvertent interchange of area i caused by area r.

3. The vector $\vec{OP}$ is also a sum of the vectors $\vec{OE}$ and $\vec{EP}$ in Fig. 3.1.

$$\begin{bmatrix} \varepsilon \\ I_i \end{bmatrix} = \begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (\varepsilon) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot (\frac{-B_s}{6} \varepsilon_i) = \vec{OE} + \vec{EP} \quad (3.15)$$

The vector $\vec{OE}$ is caused by the bias assistance provided by area i to area r. It is to be noted, however, that area r is responsible for creating it. The vector $\vec{EP}$ is also a sum of the vectors $\vec{OC}$ and $\vec{ED}$.

$$\begin{bmatrix} 0 \\ \frac{-B_s}{6} \end{bmatrix} \cdot (\varepsilon_i) = \begin{bmatrix} 1 \\ \frac{-B_r}{6} \end{bmatrix} \cdot (\varepsilon_i) + \begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (-\varepsilon_i) = \vec{OC} + \vec{ED} \quad (3.16)$$

The vector $\vec{EP}$ is created by the accumulated regulating deficiencies (seconds) ε_i of area i and $-\varepsilon_i$ of area r. Both areas are responsible for creating it by the same amount. The vector $\vec{EP}$ is the accumulated regulating deficiencies in MWH in area i.

C. Properties of Graphical Decomposition

The (ε, I_i) plane has the following properties:

1. The two lines, $I_i = \frac{B_i}{6}\varepsilon$ and $I_i = \frac{-B_r}{6}\varepsilon$, are of significance in graphical decomposition. The signs of ε_i and ε_r are dependent upon the location of the operating point (ε, I_i). This is shown in Fig. 3.2 and Table 3.1. Each quadrant is divided by two plane sectors, A and B.
2. As shown in Fig. 3.1, the vector $\vec{OC}$ is the projection of the vector $\vec{OP}$ onto the line $I_i = \frac{-B_r}{6}\varepsilon$ along the line $I_i = \frac{B_i}{6}\varepsilon$. The vector $\vec{OD}$ is the projection of the vector $\vec{OP}$ onto the line $I_i = \frac{B_i}{6}\varepsilon$ along the line $I_i = \frac{-B_r}{6}\varepsilon$.
3. The vector component caused by area i should be on the line $I_i = \frac{-B_r}{6}\varepsilon$ and is illustrated on Fig. 3.3 for various locations of the initial operating points. The vector component caused by area r should be on the line $I_i = \frac{B_i}{6}\varepsilon$ and is illustrated on Fig. 3.4. The two vector components are <u>independent</u> of each other.
4. The effect on the system time deviation and the inadvertent interchange of area i is dependent upon the sign and magnitude of $\Delta\varepsilon_{ig}$, $\Delta\varepsilon_{ic}$, $\Delta\varepsilon_{rg}$, $\Delta\varepsilon_{rc}$ during the time interval $[t_1, t_2]$. This is summarized in Table 3.2.

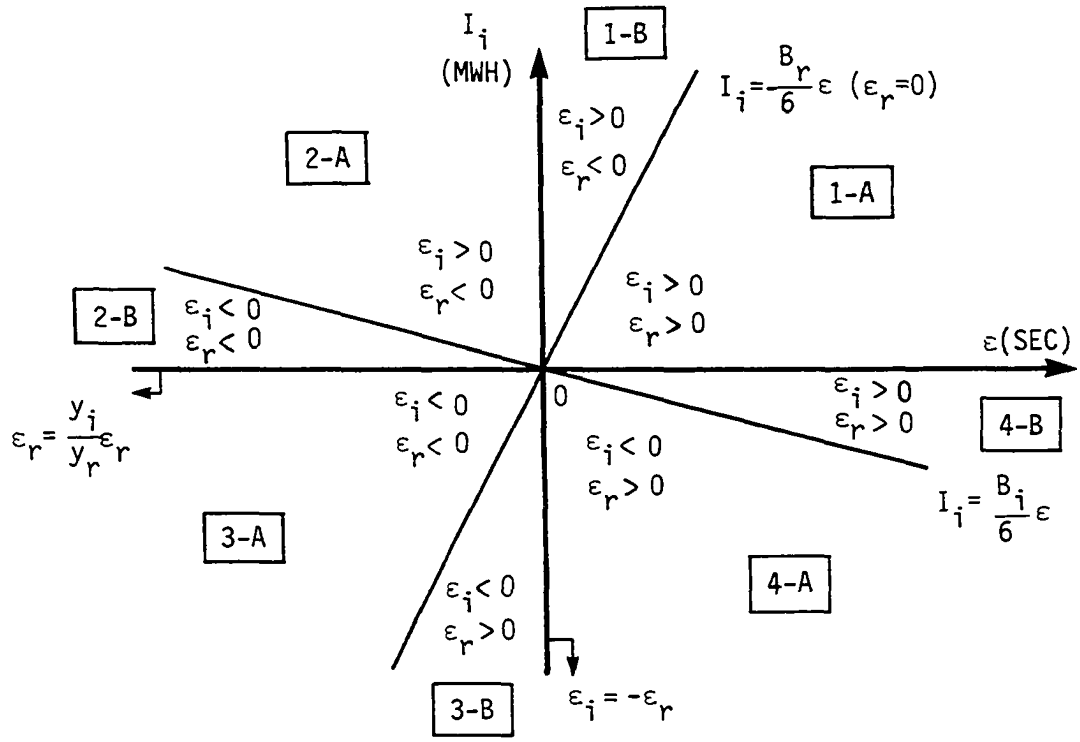


Figure 3.2 Conditions of ε_i and ε_r on the (ε, I_i) plane

Table 3.1. Conditions of ε_i and ε_r on the (ε, I_i) plane

Location of (ε, I_i)	ε_i	ε_r
1-A	+	+
1-B	+	-
2-A	+	-
2-B	-	-
3-A	-	-
3-B	-	+
4-A	-	+
4-B	+	+
Line $I_i = \frac{B_i}{6}\varepsilon$	$\varepsilon_i = 0$	
Line $I_i = \frac{-B_r}{6}\varepsilon$	$\varepsilon_r = 0$	
ε-axis	$\varepsilon_i = \frac{y_i}{y_r}\varepsilon_r$	
I_i-axis	$\varepsilon_i = -\varepsilon_r$	

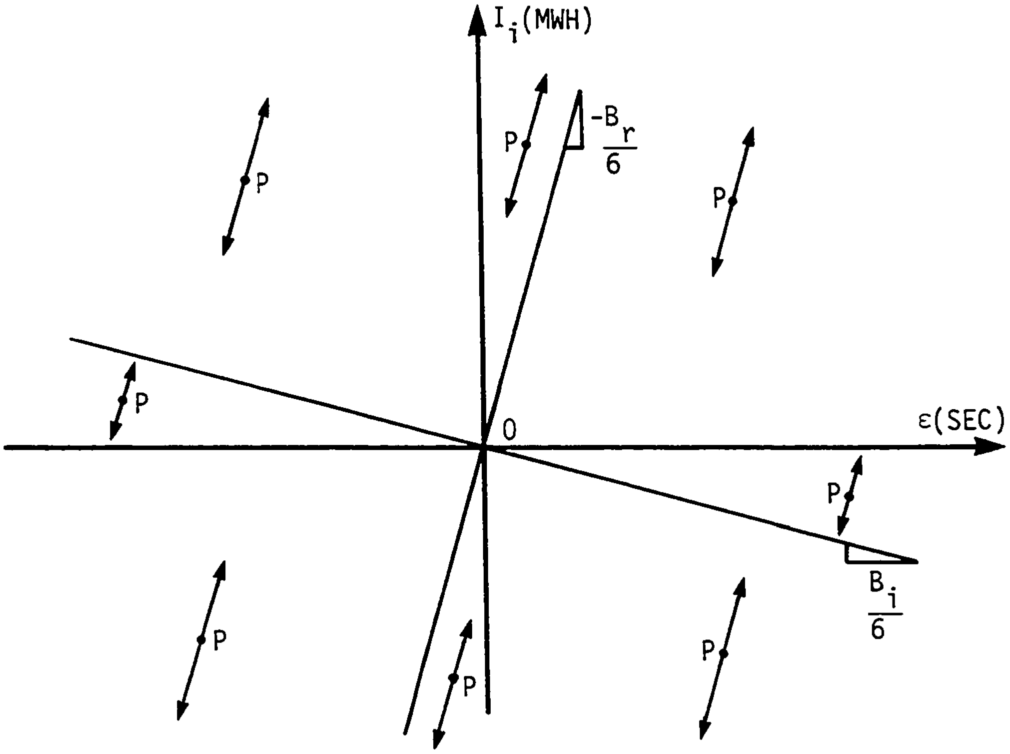


Figure 3.3. The vector component caused by $\Delta\varepsilon_{ig}$ or $\Delta\varepsilon_{ic}$

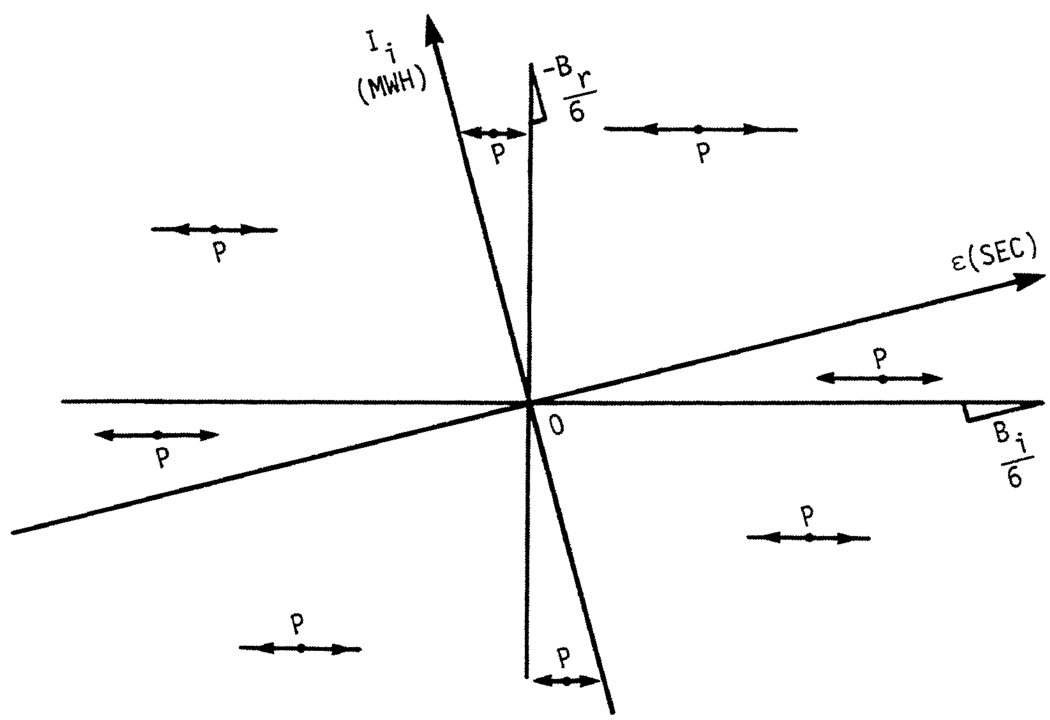


Figure 3.4. The vector component caused by $\Delta\varepsilon_{rg}$ or $\Delta\varepsilon_{rc}$

Table 3.2. The effect of $\Delta\varepsilon_{ig}$, $\Delta\varepsilon_{ic}$, $\Delta\varepsilon_{rg}$, or $\Delta\varepsilon_{rc}$ on area i[a]

Location of the Initial Operating Point	Due to $\Delta\varepsilon_{ig}$ or $\Delta\varepsilon_{ic}$						Due to $\Delta\varepsilon_{rg}$ or $\Delta\varepsilon_{rc}$					
	+			−			+			−		
	$\Delta\varepsilon$	ΔI_i	$\Delta\varepsilon_i$	$\Delta\varepsilon$	ΔI_i	$\Delta\varepsilon_i$	$\Delta\varepsilon$	ΔI_i	$\Delta\varepsilon_i$	$\Delta\varepsilon$	ΔI_i	$\Delta\varepsilon_i$
1-A, 1-B	X	X	X	0	0	0	X	0	•	0	X	•
2-A	0	X	X	X	0	0	0	0	•	X	X	•
2-B	0	X	0	X	0	X	0	0	•	X	X	•
3-A, 3-B	0	0	0	X	X	X	0	X	•	X	0	•
4-A	X	0	0	0	X	X	X	X	•	0	0	•
4-B	X	0	X	0	X	0	X	X	•	0	0	•

[a]0 means to the desired direction, X means to the undesired direction, and • means not affected.

IV. CORRECTIVE CONTROL SCHEMES

For corrective control, the intentional offset term (CORR) is imposed in the area control error signal of an area, as shown in Eq. 3.2. The sign and magnitude of the term (CORR) depends on the intial value of the signal to be corrected (i.e., on $\varepsilon(t_1)$, $I_i(t_1)$ or $\varepsilon_i(t_1)$ for area i). The sign of the term (CORR) should be opposite to that of the initial value of that signal.

Equation 3.9b shows that, for any area i, $\Delta\varepsilon_{ic}$ is the product of the time integral of the term $(CORR)_i$ and a common factor ($\frac{-6}{B_S}$) over a given time interval $[t_1,t_2]$. Assuming that the sign of the term $(CORR)_i$ does not change in the interval, the sign of $\Delta\varepsilon_{ic}$ is the same as that of $(CORR)_i$.

The effect of the corrective control is investigated in the following sequence.

(a) The effect of either $\Delta\varepsilon_{ic}$ or $\Delta\varepsilon_{rc}$, and

(b) The effect of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ when there is a specific relationship between the two, introduced by the inter-area or system-wide coordination.

A. Applying Correction to Area i or Area r Alone

It is assumed that, during the time interval $[t_1,t_2]$, the operating point lies in the same sector of the (ε,I_i) plane as that of the initial operating point P. Then, the following observations, derived from Table 3.2 and Fig. 3.3, can be made on the unilateral effect of $\Delta\varepsilon_{ic}$ on area i.

1. We first consider when the initial operating point P is in the <u>first</u> or <u>third</u> quadrant of the (ε, I_i) plane. If the term $(CORR)_i$ has a sign such that it tends to correct any one signal (e.g., ε, I_i, or ε_i), the other signals are simultaneously corrected.

2. Next, we consider when the initial operating point P is in the <u>second</u> or <u>fourth</u> quadrant of the (ε, I_i) plane. If the term $(CORR)_i$ has a sign such that it tends to correct any one signal, the other signals could be simultaneously aggravated. The following situations may occur:

   a) If $(CORR)_i$ is implemented in the direction to correct I_i, ε is aggravated but ε_i is corrected when the point P is in the 2-A or 4-A sector. On the other hand, both ε and ε_i are aggravated when the point P is in the 2-B or 4-B sector. This is illustrated in Fig. 4.1.

   b) If the sign of $(CORR)_i$ is in the direction to correct ε, both I_i and ε_i are aggravated when the point P is in the 2-A or 4-A sector. However, when the point P is in the 2-B or 4-B sector, I_i is aggravated, but ε_i is simultaneously corrected. This is illustrated in Fig. 4.2.

   c) If the sign of $(CORR)_i$ is in the direction to correct ε_i, ε is aggravated but I_i is corrected when the point P is in the 2-A or 4-A sector. However, when the point P is in the 2-B or 4-B sector, I_i is aggravated but ε

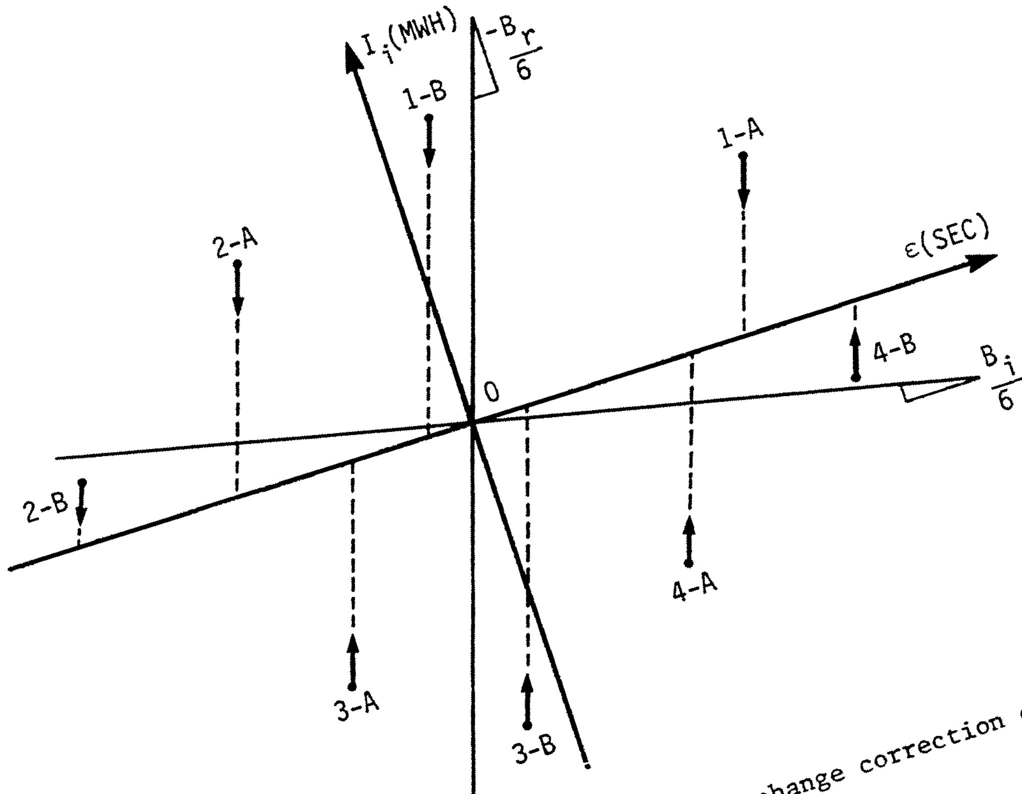


Figure 4.1. The effect of inadvertent interchange correction on area i

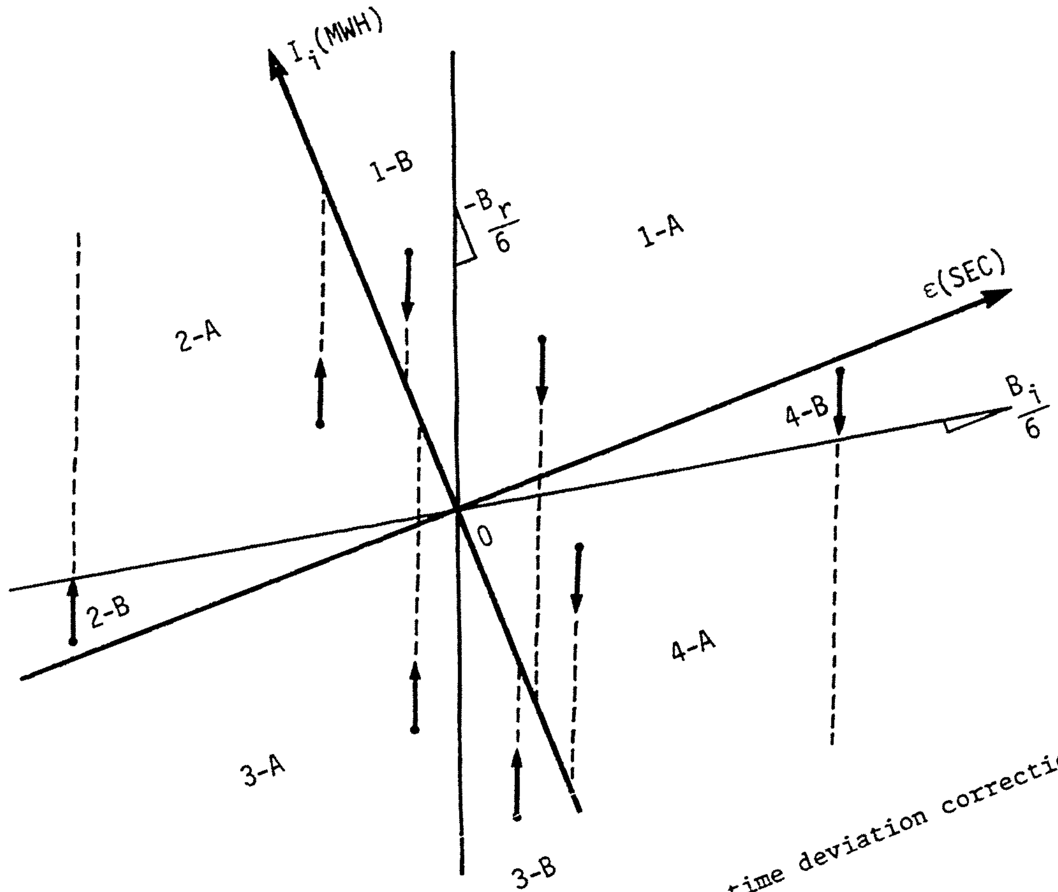


Figure 4.2 The effect of system time deviation correction on area i

is simultaneously corrected. This is illustrated in Fig. 4.3.

Noting that ε_i is not affected by $\Delta\varepsilon_{rc}$, from Table 3.2 and Fig. 3.4, we can also make the following observations on the effect of $\Delta\varepsilon_{rc}$ on area i:

1. When the initial operating point P is in the <u>second</u> or <u>fourth</u> quadrant of the (ε, I_i) plane, both ε and I_i are corrected or aggravated simultaneously depending on the sign of $\Delta\varepsilon_{rc}$.
2. When the initial operating point P is in the <u>first</u> or <u>third</u> quadrant of the (ε, I_i) plane, if any one signal (ε or I_i) is corrected, the other signal is aggravated, depending on the sign of $\Delta\varepsilon_{rc}$.

B. The Effect of Simultaneous Application of Correction

The effect of simultaneous application of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ on area i is investigated when there is a specific relationship between the two introduced by the inter-area coordination. The offset terms $(CORR)_i$ and $(CORR)_r$ are assumed not to change signs during the time interval $[t_1, t_2]$. The signs of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ are the same as those of $(CORR)_i$ and $(CORR)_r$, respectively. It is also assumed that the operating point lies in the same sector of the (ε, I_i) plane as that of the initial operating point P during the time interval. The following observations can be made.

1. We first examine the bilateral inadvertent interchange correction scheme and the system time deviation correction scheme. These

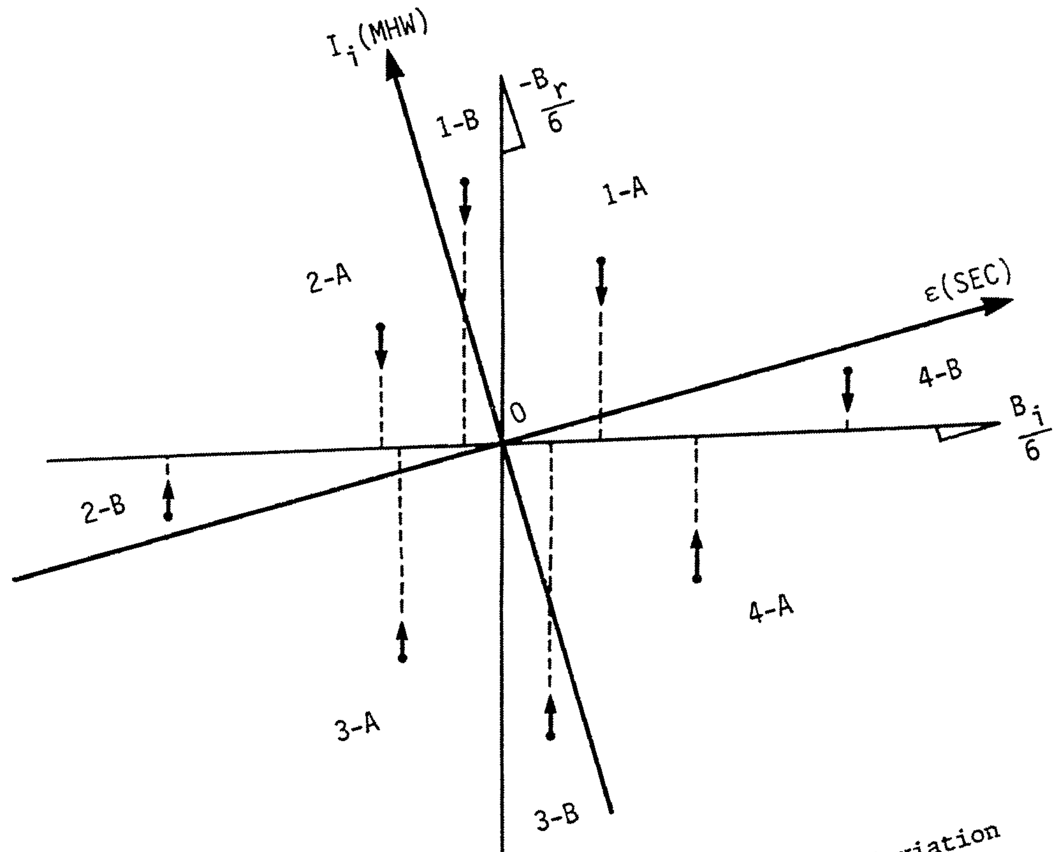


Figure 4.3. The effect of area time deviation component correction on area i

two schemes, which are commonly used in the North American Interconnection, complement each other.

a) If the same correction is implemented in and outside area i, i.e., $(CORR)_i = -(CORR)_r$. By the definitions in Eq. 3.9b and 3.9d, $\Delta\varepsilon_{ic} = -\Delta\varepsilon_{rc}$. Then we can write

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{ic} \\ \Delta\varepsilon_{rc} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \left(- \frac{B_s}{6} \Delta\varepsilon_{ic}\right) \tag{4.1}$$

Equation 4.1 shows that if only $\Delta\varepsilon_{ic}$ is used, there is no change in the system time deviation, but only the inadvertent interchange energy of area is affected. This is the basis of the bilateral inadvertent interchange correction scheme. This is illustrated in Fig. 4.4.

$$\Delta\varepsilon_{rc} = \sum_{\substack{j=1 \\ j\neq i}}^{Q} \Delta\varepsilon_{jc} = -\Delta\varepsilon_{ic} \tag{4.2}$$

There are many ways for selecting $\Delta\varepsilon_{jc} (j\neq i)$ to satisfy Eq. 4.2. One case is for any area j $(j\neq i)$ to set $(CORR)_j = -(CORR)_i$ and for any other area $K(K\neq i,j)$ to set $(CORR)_K = 0$. In addition, if each of the areas sets its correction term proportional to the initial value of its own inadvertent interchange energy, Eq. 4.2 is also satisfied.

$$(CORR)_r = \sum_{\substack{j=1 \\ j\neq i}}^{Q} (CORR)_j = C \cdot \sum_{\substack{j=1 \\ j\neq i}}^{Q} I_j(t_1) = -C \cdot I_i(t_1) = -(CORR)_i \tag{4.3}$$

where C is a constant.

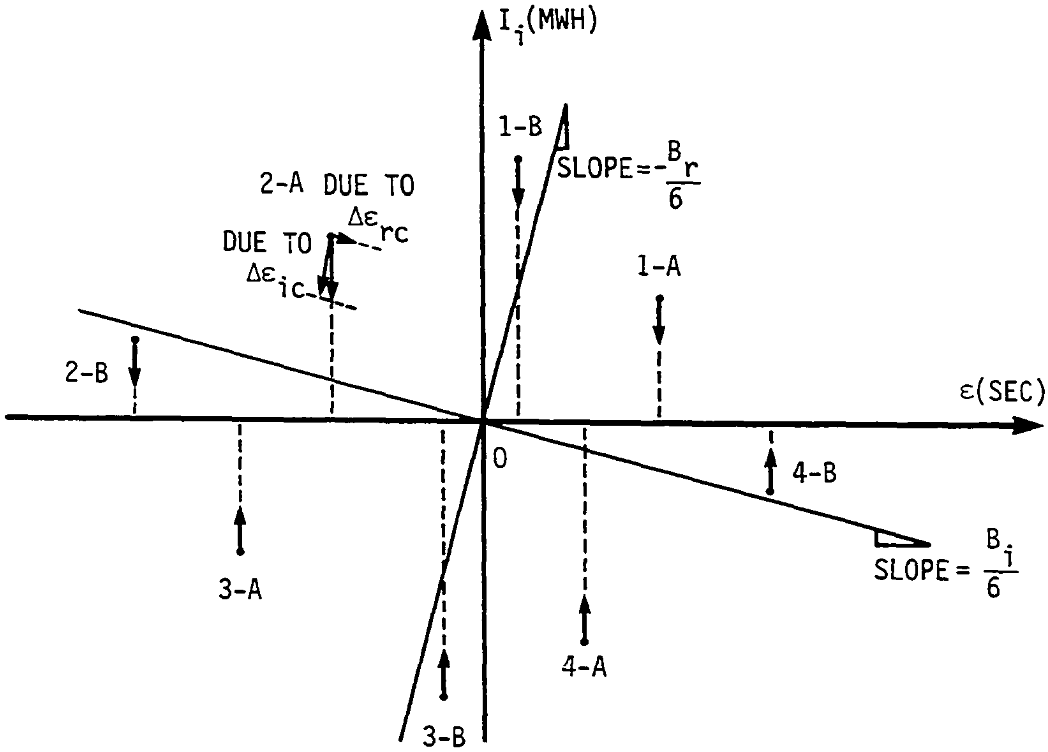


Figure 4.4. Bilateral inadvertent interchange correction

b) If the correction term of an area is proportional to its bias size, i.e., $(CORR)_i/(CORR)_r = y_i/y_r$. Then, $\Delta\varepsilon_{ic}/\Delta\varepsilon_{rc} = y_i/y_r$. Then, the effect of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ can be written as

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{ic} \\ \Delta\varepsilon_{rc} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot (\frac{1}{y_i} \Delta\varepsilon_{ic}) \tag{4.4}$$

Equation 4.4 shows that if only $\Delta\varepsilon_{ic}$ is used, there is no change in the inadvertent interchange, but only the system time deviation is affected. If each of the areas set its own offset term proportional to the product of the initial value of system time deviation and its own bias setting, then we have

$$(CORR)_r = \sum_{\substack{j=1 \\ j\neq i}}^{Q} (CORR)_j = C \cdot \sum_{\substack{j=1 \\ j\neq i}}^{Q} B_j\varepsilon(t_1) = C \cdot B_r\varepsilon(t_1) \tag{4.5a}$$

$$(CORR)_i = C \cdot B_i \cdot \varepsilon(t_1) \tag{4.5b}$$

Then,

$$\frac{(CORR)_i}{(CORR)_r} = \frac{B_i}{B_r} = \frac{y_i}{y_r} \tag{4.5c}$$

This scheme is relevant to the analysis of the continuous automatic system time deviation correction scheme adopted by the WSCC system. If all areas set their own offset term proportional to the product of the prevailing system time deviation and their own bias setting, then the correction term of area r is given by

$$(CORR)_r = \sum_{\substack{j=1 \\ j\neq i}}^{Q} (CORR)_j = C \cdot \sum_{\substack{j=1 \\ j\neq i}}^{Q} B_j\varepsilon(\tau) = C \cdot B_r\varepsilon(\tau) \tag{4.6a}$$

where τ is the prevailing time and $\tau\varepsilon[t_1,t_2]$.

Equation 4.5c also holds for the continuous automatic system time deviation correction scheme if all areas are participating in corrective control. This is the basis of the system time deviation correction scheme. It is illustrated in Fig. 4.5.

c) If the correction terms in and outside area i satisfy the relation $\Delta\varepsilon_{ic} = -\Delta\varepsilon_{rc} = (-\frac{6}{B_s}) \cdot (-I_i(t_1))$ in Eq. 4.1, then

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot (-I_i(t_1)) \qquad (4.7)$$

If $\Delta\varepsilon_{ic} = -y_i\varepsilon(t_1)$ and $\Delta\varepsilon_{rc} = -y_r\varepsilon(t_1)$ in Eq. 4.4, then

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot (-\varepsilon(t_1)) \qquad (4.8)$$

The effect of two-step correction scheme is illustrated in Fig. 4.6. The vector in Eq. 4.7 is $\vec{PA}$ and the vector in Eq. 4.8 is $\vec{PB}$.

$$\vec{PO} = \vec{PA} + \vec{PB} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot (-I_i(t_1)) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot (-\varepsilon(t_1))$$

$$= \begin{bmatrix} -\varepsilon(t_1) \\ -I_i(t_1) \end{bmatrix} \qquad (4.9)$$

The basis vectors defined by the two-step correction scheme are the same as those shown in Eq. 3.13.

2. We next examine correction schemes based on the components of time deviation. Let $(CORR)_i/(CORR)_r = \varepsilon_i(t_1)/\varepsilon_r(t_1)$. Then,

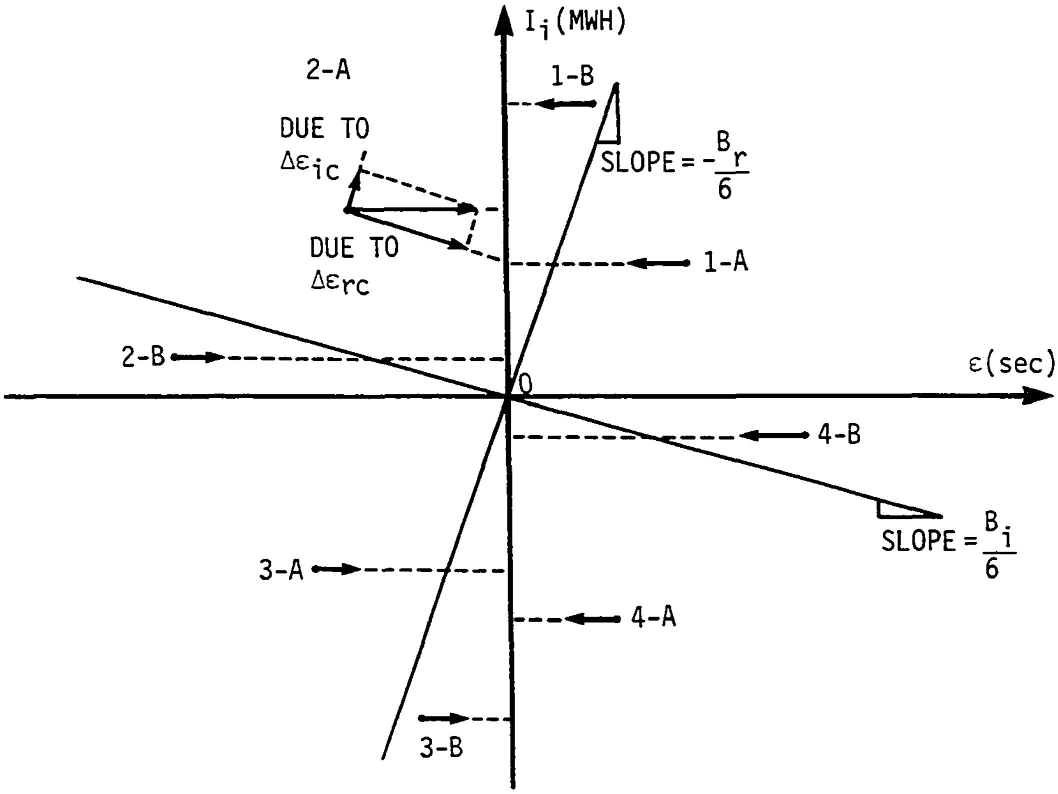
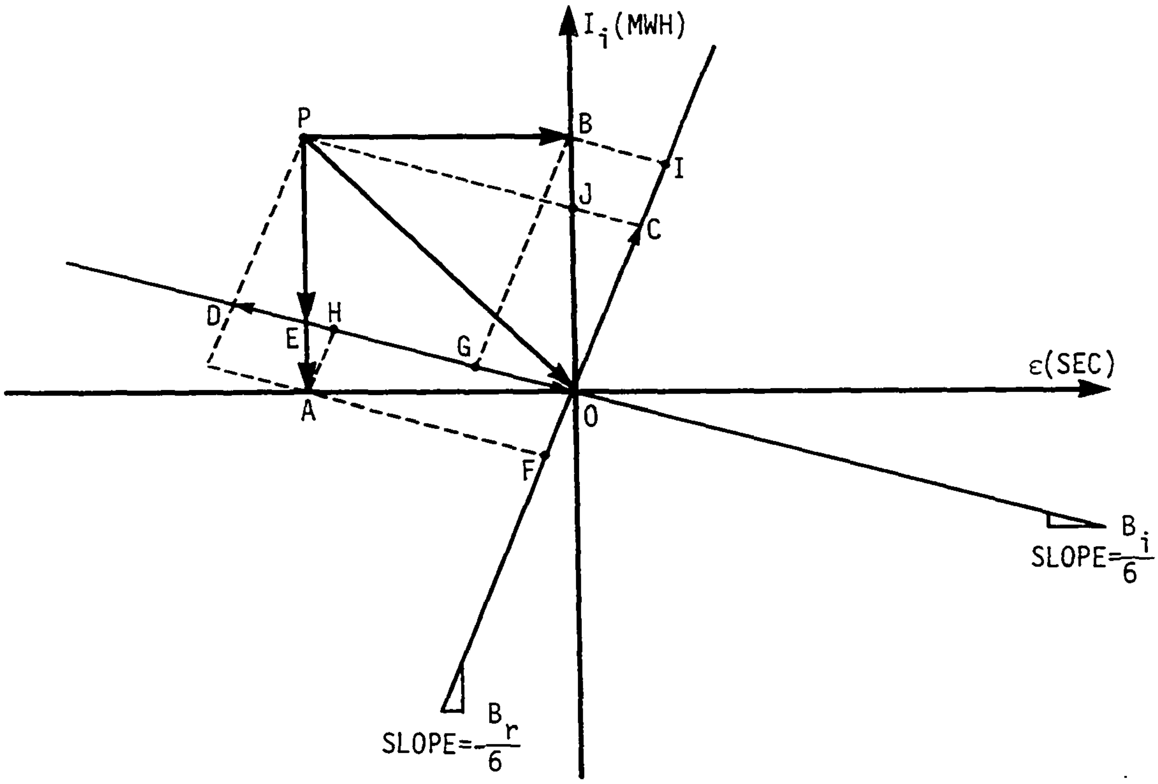


Figure 4.5. System time deviation correction (system-wide)



PO: (1)	$\vec{PA}+\vec{PB}$	$\vec{PA}=\vec{CF}+\vec{DH}$ $\vec{PB}=\vec{CI}+\vec{DG}$	BASIS VECTORS $\begin{bmatrix}1\\0\end{bmatrix},\begin{bmatrix}0\\1\end{bmatrix}$
(2)	$\vec{PD}+\vec{PC}$	$\vec{PD}=\vec{CO}$ $\vec{PC}=\vec{DO}$	BASIS VECTORS $\begin{bmatrix}1\\ \frac{-B_r}{6}\end{bmatrix},\begin{bmatrix}1\\ \frac{B_i}{6}\end{bmatrix}$
(3)	$\vec{PE}+\vec{EO}$	$\vec{PE}=\vec{CO}+\vec{DE}$	BASIS VECTORS $\begin{bmatrix}0\\1\end{bmatrix},\begin{bmatrix}1\\ \frac{B_i}{6}\end{bmatrix}$

Figure 4.6. The effect of the corrective controls

$\Delta\varepsilon_{ic}/\Delta\varepsilon_{rc} = \varepsilon_i(t_1)/\varepsilon_r(t_1)$. Then, the effect of the correction on ε and I_i can be written as

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{ic} \\ \Delta\varepsilon_{rc} \end{bmatrix} = \begin{bmatrix} \varepsilon(t_1) \\ I_i(t_1) \end{bmatrix} \cdot \left(\frac{\Delta\varepsilon_{ic}}{\varepsilon_i(t_1)} \right) \tag{4.10}$$

If all areas set their own correction term to be proportional to the initial value of the area component of the system time deviation,

$$(\mathrm{CORR})_r = \sum_{\substack{j=1 \\ j\neq i}}^{Q} (\mathrm{CORR})_j = C \cdot \sum_{\substack{j=1 \\ j\neq i}}^{Q} \varepsilon_j(t_1) = C \cdot \varepsilon_r(t_1) \tag{4.11a}$$

$$(\mathrm{CORR})_i = C \cdot \varepsilon_i(t_1) \tag{4.11b}$$

Then,

$$\frac{(\mathrm{CORR})_i}{(\mathrm{CORR})_r} = \frac{\varepsilon_i(t_1)}{\varepsilon_r(t_1)} \tag{4.11c}$$

Equation 4.10 shows that both the system deviation and the inadvertent interchange energy can be corrected simultaneously along the path $\overrightarrow{PO}$ (Fig. 4.6). This is the basis of the synchronized coordinated correction scheme suggested by Cohn [7]. It is illustrated in Fig. 4.7.

If $\Delta\varepsilon_{ic} = -\varepsilon_i(t_1)$ and $\Delta\varepsilon_{rc} = -\varepsilon_r(t_1)$, then the vector in Eq. 4.10 becomes

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 \\ \frac{-B_r}{6} \end{bmatrix} \cdot (-\varepsilon_i(t_1)) + \begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (-\varepsilon_r(t_1)) = \overrightarrow{PD} + \overrightarrow{PC}$$

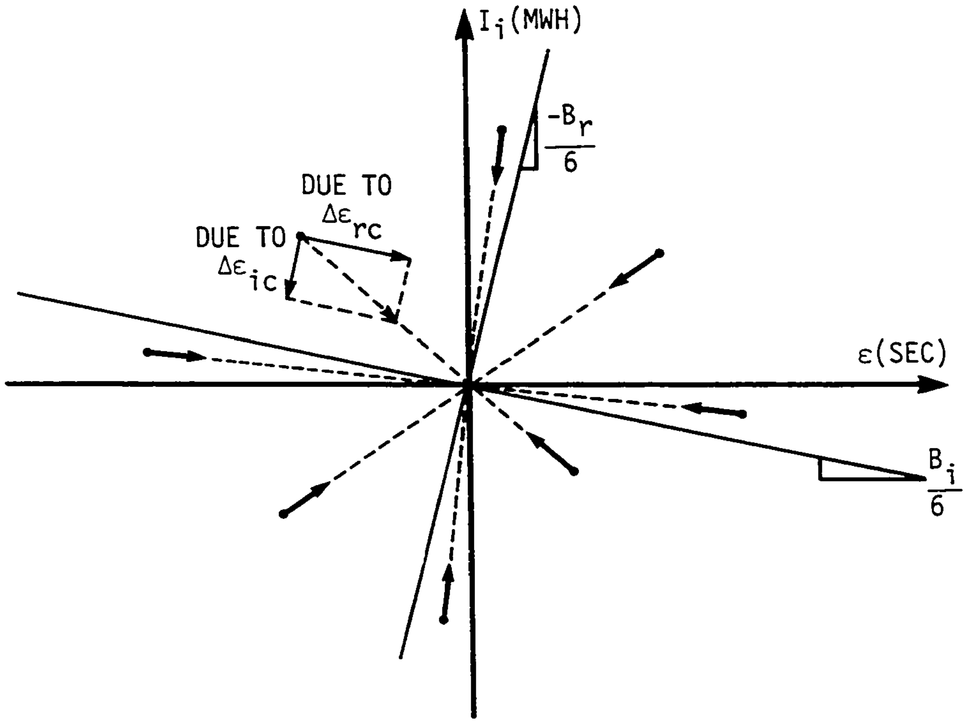


Figure 4.7. The effect of synchronized, coordinated correction on area i

$$= \begin{bmatrix} -\varepsilon(t_1) \\ -I_i(t_1) \end{bmatrix} = \vec{PO} \qquad (4.12)$$

Equation 4.12 shows that the synchronized coordinated correction scheme produces the same effect as the two-step corrective scheme given by Eq. 4.9. This is also illustrated in Fig. 4.6. The basis vectors defined by this scheme are the same as those shown in Eq. 3.14.

3. The effect of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ due to various correction schemes is summarized in Table 4.1. The following observations can be made:

   a) When an area whose operating point is in the 2-B or 4-B sector of the (ε, I_i) plane is reducing its inadvertent interchange bilaterally (with other area j whose operating point is in third or first quadrant of the (ε, I_j) plane), the area component of the system time deviation is aggravated (Fig. 4.4).

   b) When an area whose operating point is on the 2-A or 4-A sector of the (ε, I_i) plane is participating in the correction of the system time deviation, the area component of the system time deviation is aggravated (Fig. 4.5).

   c) From Eqs. 4.9 and 4.12, when both system-wide bilateral inadvertent interchange energy and system time deviation correction schemes are used as a two-step procedure, they produce the same effect as the one-step synchronized,

Table 4.1. The effect of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ on area i[a]

Location of the Initial Operating Point		Bilateral Inadvertent Interchange Correction				System Time Deviation Correction				Synchronized Coordinated Correction			
		$\Delta\varepsilon_i = -\Delta\varepsilon_r$				$\Delta\varepsilon_{ic}/\Delta\varepsilon_{rc} = y_i/y_r$				$\Delta\varepsilon_{ic}/\Delta\varepsilon_{rc} = \varepsilon_i(t_1)/\varepsilon_r(t_1)$			
		$\Delta\varepsilon_i$	ε	I_i	ε_i	$\Delta\varepsilon_i$	ε	I_i	ε_i	$\Delta\varepsilon_i$	ε	I_i	ε_i
	2-A	–	•	0	0	+	0	•	X	–	0	0	0
$\varepsilon<0$	2-B	–	•	0	X	+	0	•	0	+	0	0	0
	3-A,3-B	+	•	0	0	+	0	•	0	+	0	0	0
	4-A	+	•	0	0	–	0	•	X	+	0	0	0
$\varepsilon<0$	4-B	+	•	0	X	–	0	•	0	–	0	0	0
	1-A,1-B	–	•	0	0	–	0	•	0	–	0	0	0

[a]0 means corrected to the desired direction, X means to the undesired direction, and • means not affected.

coordinated correction scheme. In other words, from Fig. 4.6, the same vector PO can be represented as

$$\overrightarrow{PO} = \overrightarrow{PA} + \overrightarrow{PB} \text{ (two-step)} \tag{4.13a}$$

$$\overrightarrow{PO} = \overrightarrow{PD} + \overrightarrow{PC} \text{ (one-step)} \tag{4.13b}$$

d) However, the sum of the magnitude of the components $\sum_{i=1}^{Q} |\Delta\varepsilon_{ic}|$ is different for the two-step and the one-step correction schemes. As pointed out in a) and b), an area may have to regulate in the wrong direction depending on the location of the initial operating point. This was already pointed out by Cohn [4].

C. Comparison of Corrective Control Schemes

The corrective control schemes reviewed in Section B are compared in terms of energy required for the control action. This energy is given by $\int_{t_1}^{t_2}$ (CORR)dt. This integral can be evaluated from Eq. 3.9b. Rearranging Eq. 3.9b, we get

$$\int_{t_1}^{t_2} (\text{CORR})_i dt = (-\frac{B_s}{6}) \cdot \Delta\varepsilon_{ic} \tag{4.14}$$

Thus, the amount of energy (in MWH) required for the control action is defined as $(-B_s/6) \cdot |\Delta\varepsilon_{ic}|$ for area i. For the interconnected system, the total amount of energy (in MWH) required for the control action is given by $(-B_s/6) \cdot \sum_{i=1}^{Q} |\Delta\varepsilon_{ic}|$.

The sign and magnitude of $\Delta\varepsilon_{ic}$ are dependent upon each control scheme. After the control action, the operating points for all areas are assumed to return to the origin. The following corrective control schemes are considered:

(a) Two-step correction schemes.

(b) One-step synchronized coordinated correction scheme.

1. The energy required for the control action of the system wide bilateral inadvertent interchange energy and the system time correction schemes are calculated as follows:

   a) For the system wide bilateral inadvertent interchange energy correction, any area i should set $\Delta\varepsilon_{ic} = (-6/B_s) \cdot (-I_i(t_1))$. The energy required for this corrective control area i becomes

   $$(-B_s/6)\cdot|\Delta\varepsilon_{ic}| = |-I_i(t_1)| \qquad (4.15)$$

   b) For the time deviation correction, any area i should set $\Delta\varepsilon_{ic} = -y_i \cdot \varepsilon(t_1)$. The energy required for this corrective control area i becomes

   $$(-B_s/6)\cdot|\Delta\varepsilon_{ic}| = |(B_i/6)\varepsilon(t_1)| \qquad (4.16)$$

   c) The energy required for the two-step correction scheme becomes the sum of those of Eqs. 4.15 and 4.16.

   $$|-I_i(t_1)| \;\div\; |(B_i/6)\varepsilon(t_1)| \qquad (4.17)$$

   Using the inequality $(|x|+|y|\geq|x+y|)$,

   $$|-I_i(t_1)| + |(B_i/6)\varepsilon(t_1)| \geq |-I_i(t_1) + (B_i/6)\varepsilon(t_1)| =$$
   $$(-B_s/6) \cdot |-\varepsilon_i(t_1)| \qquad (4.18)$$

If the initial operating point P is in <u>the third or first quadrant</u>, both $I_i(t_1)$ and $\varepsilon(t_1)$ have the same sign and, hence, the equality in Eq.

4.18 holds. However, if the initial operating point P is in the second or fourth quadrant, $I_i(t_1)$ has the opposite sign to that of $\varepsilon(t_1)$ and, hence, the equality in Eq. 4.18 does not hold. The energy required for the two-step correction scheme is larger than the absolute value of its initial regulating deficiencies.

d) The total amount of energy required for the two-step correction scheme is given by

$$\sum_{i=1}^{Q} \left(|-I_i(t_1)| + \left|\frac{B_i}{6}\,\varepsilon(t_1)\right|\right) = \sum_{i=1}^{Q} |-I_i(t_1)| + \left(\frac{-B_s}{6}\right)\cdot|\varepsilon(t_1)| \tag{4.19}$$

$$\sum_{i=1}^{Q} |-I_i(t_1)| + \left(\frac{-B_s}{6}\right)\cdot|\varepsilon(t_1)| \geq \left(\frac{-B_s}{6}\right)\cdot\sum_{i=1}^{Q} |-\varepsilon_i(t_1)| \tag{4.20}$$

2. For the system-wide synchronized coordinated correction, any area i should set $\Delta\varepsilon_{ic} = -\varepsilon_i(t_1)$. The energy required for this corrective control for area i becomes

$$\left(\frac{-B_s}{6}\right)\cdot|\Delta\varepsilon_{ic}| = \left(\frac{-B_s}{6}\right)|-\varepsilon_i(t_1)| \tag{4.21}$$

The total amount of energy required for this corrective control in the interconnected system becomes

$$\left(\frac{-B_s}{6}\right)\sum_{i=1}^{Q} |-\varepsilon_i(t_1)| \tag{4.22}$$

3. Comparing Eqs. 4.20 and 4.22, the energy required for the two-step correction scheme is not less than that required for one-step synchronized coordinated correction scheme.

Table 4.2 shows the regulation survey of the Eastern Interconnected System cited in Reference 4. An example of

Table 4.2. Regulation survey of Eastern Interconnected System (0700 CST, January 11, 1977)[a]

Region	Bias Setting B_i (MW/.1Hz)	Inadvertent Energy I_i (MWH)	ε_i (sec)	Location
1	- 940	644	.18861	2-A
2	- 420	223	.01147	2-A
3	-1087	-179	- .82055	3-A
4	-1180	-1205	-2.0215	3-A
5	- 639	141	- .20550	2-B
6	-1080	376	- .19250	2-B
Total	-5336	0	-3.040	

[a]System time deviation is -3.04 sec.

calculating the energy required for the two-correction scheme is shown in Table 4.3. For the two-step correction scheme, the total amount of energy is 5471.6 MWH, while only 3059.44 MWH is required for the synchronized coordinated correction scheme. Thus, the two-step correction scheme involves an unnecessary regulation. The two-step correction scheme can be modified in order to eliminate unnecessary regulation. This can be accomplished as follows:

a) An area whose initial operating point is in the 2-A (or 4-A) sector of the (ε, I_i) plane can arrange bilateral inadvertent interchange correction with any other area whose initial operating point is in the third (or first) quadrant. The arrangement should be implemented such the line $I_i = \frac{B_i}{6}\varepsilon$ or ε-axis should not be crossed. However, an area whose initial operating point is in the 2-B (or 4-B) sector should not participate in inadvertent interchange correction. This is illustrated in Fig. 4.8.

b) An area whose initial operating point is in the 2-A (or 4-A) sector of the (ε, I_i) plane should not participate in the system time deviation correction. An area whose initial operating point is not in the 2-A (or 4-A) sector should correct its own area component of system time deviation. The scheme should be arranged such that

Table. 4.3. The amount of regulation (MWH) for each correction scheme

Region	Two-Step Correction		Synchronized Coordinated Correction	Modified Two-Step Correction	
	(1)[a]	(2)[b]		(3)[c]	(4)[d]
	$(\frac{-B_s}{6})\cdot\Delta\varepsilon_{ic}$	$(\frac{-B_s}{6})\cdot\Delta\varepsilon_{ic}$	$(\frac{-B_s}{6})\cdot\Delta\varepsilon_{ic}$	$(\frac{-B_s}{6})\cdot\Delta\varepsilon_{ic}$	$(\frac{-B_s}{6})\cdot\Delta\varepsilon_{ic}$
1	-644	467.27	-167.74	-167.74	0
2	-223	212.80	- 10.20	- 10.20	0
3	179	550.75	729.74	10.20	719.54
4	1205	592.80	1797.80	167.74	1630.06
5	-141	323.76	182.76	0	182.76
6	-376	547.20	171.20	0	171.20
$(\frac{-B_s}{6})\sum_{i=1}^{Q}\lvert\Delta\varepsilon_{ic}\rvert$	2768	2703.6		355.88	2703.56
	5471.6		3059.44	3059.44	

[a]System-wide inadvertent interchange correction.

[b]System time deviation correction.

[c]Modified inadvertent interchange correction.

[d]Modified system time deviation correction.

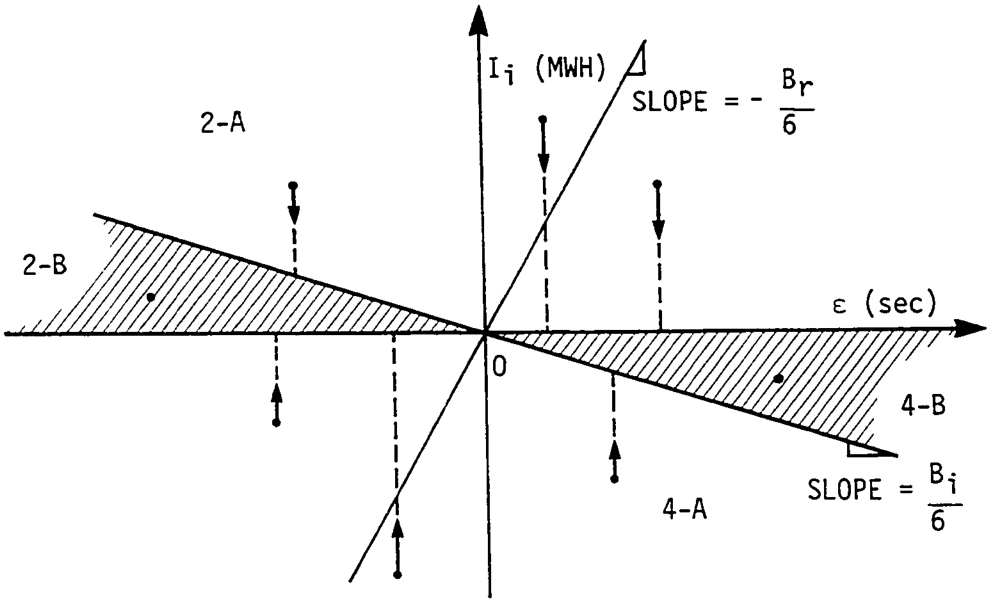


Figure 4.8 Modified bilateral inadvertent interchange correction scheme

the lines $I_i = \frac{B_i}{6} \varepsilon$ or I_i-axis are not crossed. This is illustrated in Fig. 4.9.

4. In the two-step correction scheme, the amount of energy required for the control action by each area is the same as the absolute value of its initial regulating deficiencies at the initial operating point.

Columns 5 and 6 of Table 4.3 show an example calculation of the amount of energy required for the control action of each area in the modified two-step correction scheme. Bilateral inadvertent interchange correction is arranged between areas 1 and 4 and areas 2 and 3 prior to system time deviation correction. After bilateral inadvertent interchange correction, areas 3, 4, 5, and 6 correct their components of the system time deviation.

It is to be noted that for the modified two-step correction scheme, the total amount of energy required for the control action is 3059.44 MWH, which is the same as that required by the synchronized coordinated correction. Thus, the modified two-step correction scheme can produce the same effect as the present two-step correction scheme with less amount of system regulation.

D. Causes of Excessive Accumulation of Inadvertent Interchange Energy

In Section A, B, and C of this chapter, schemes for applying the offset correction terms $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ have been introduced. Their effects, when applied singly or simultaneously on the system time

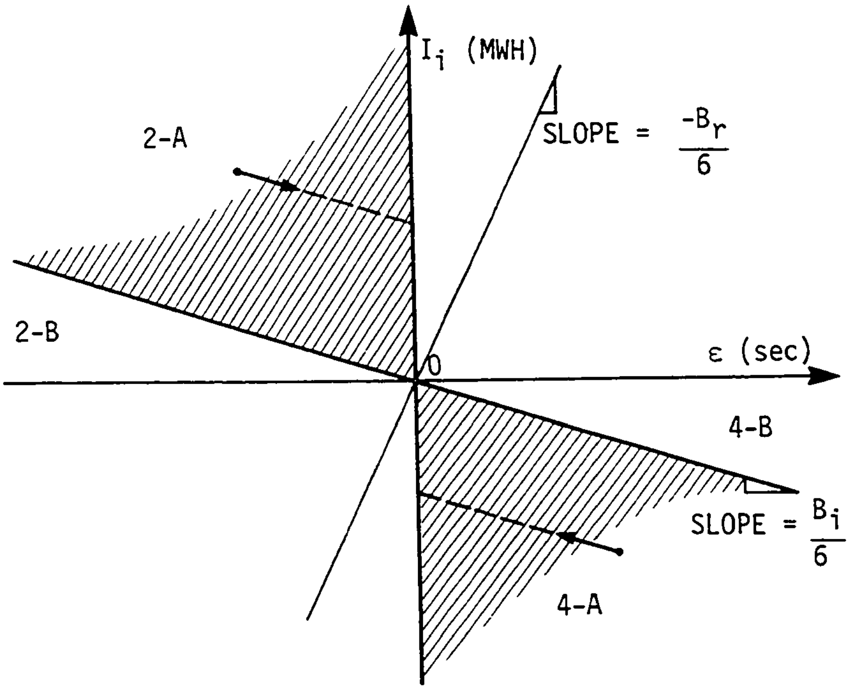


Figure 4.9 Modified system time deviation correction scheme

deviation and inadvertent interchange energy have been presented. In this section, the effects of the AGC regulating deficiency terms $\Delta\varepsilon_{ig}$ and $\Delta\varepsilon_{rg}$ are explored. Again, these effects are considered singly or together. They are superimposed on the effects of $\Delta\varepsilon_{ic}$ and/or $\Delta\varepsilon_{rc}$.

We begin by investigating the problem of the accumulation of inadvertent interchange energy experienced in the WSCC system. The WSCC system uses the continuous automatic time deviation correction scheme. An area always has the offset term that is proportional to the product of the prevailing system time deviation and its own bias setting, as shown in Eq. 4.6. The constant C is .1. For a given time interval $[t_1,t_2]$,

$$\Delta\varepsilon_{ic} = (-.6)\ y_i \int_{t_1}^{t_2} \varepsilon(\tau)d\tau \qquad (4.23a)$$

$$\Delta\varepsilon_{rc} = (-.6)\ y_r \int_{t_1}^{t_2} \varepsilon(\tau)d\tau \qquad (4.23b)$$

Then, from Eqs. 3.9 and 3.10,

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{ig} \\ \Delta\varepsilon_{rg} \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{ic} \\ \Delta\varepsilon_{rc} \end{bmatrix} \qquad (4.24a)$$

$$= \begin{bmatrix} 1 & 1 \\ \frac{-B_r}{6} & \frac{B_i}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{ig} \\ \Delta\varepsilon_{rg} \end{bmatrix} + \begin{bmatrix} (-.6)\int_{t_1}^{t_2} \varepsilon(\tau)d\tau \\ 0 \end{bmatrix} \qquad (4.24b)$$

Let area i be the area of interest. The possible situations that can lead to an increase of inadvertent interchange of area i are investigated. Let the initial operating point of area i be the point A in sector 2-A of the (ε, I_i) plane (Fig. 4.10).

At $t=t_2$, the operating point due to $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ is moved to point D if all areas participate in the continuous automatic time deviation scheme simultaneously (Fig. 4.10). If some areas in the interconnection do not participate, then Eq. 4.23b becomes

$$\Delta\varepsilon'_{rc} = -.6\, y'_r \int_{t_1}^{t_2} \varepsilon(\tau)d\tau \qquad (4.25)$$

where $y'_r < y_r$ and y'_r is the sum of bias ratios of areas in the rest of the interconnection that participate in the correction scheme.

At $t=t_2$, the operating point due to $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon'_{rc}$ is moved to point D'. The following operating points can be reached at $t=t_2$ and illustrated in Fig. 4.10, depending upon $\Delta\varepsilon_{ig}$ and $\Delta\varepsilon_{rg}$.

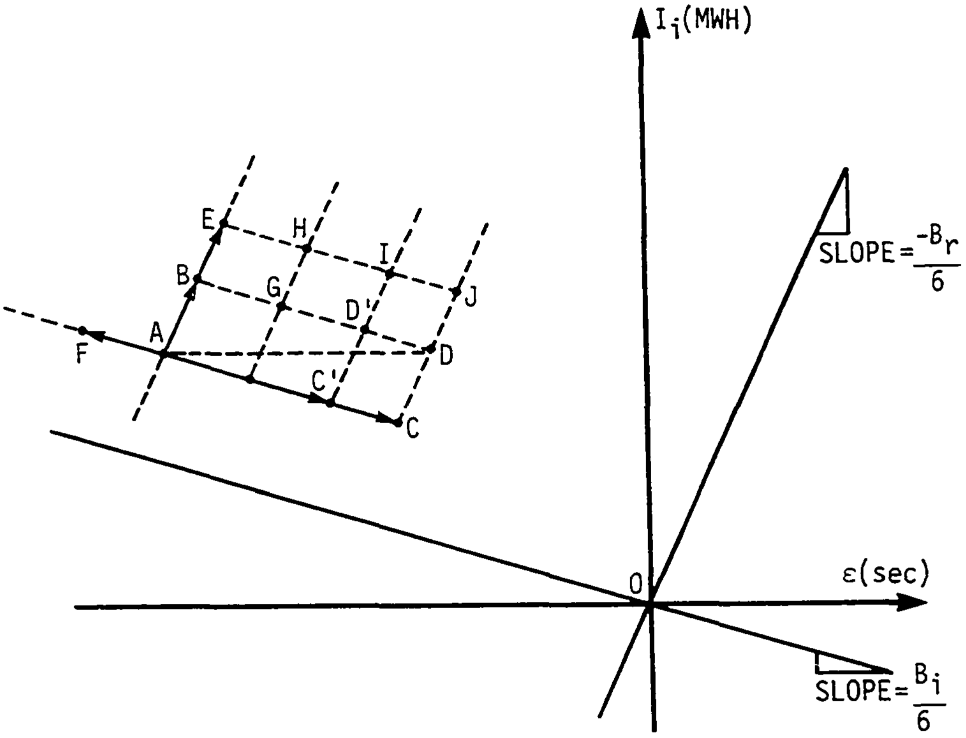
G: $\Delta\varepsilon_{ig} = 0$ and $\Delta\varepsilon_{rg}$ has the opposite sign of $\Delta\varepsilon_{rc}$.

H: $\Delta\varepsilon_{ig}$ has the same sign as $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rg}$ has the opposite sign to $\Delta\varepsilon_{rc}$.

I: $\Delta\varepsilon_{rg} = 0$, and $\Delta\varepsilon_{ig}$ has the same sign as $\Delta\varepsilon_{ic}$.

J: $\Delta\varepsilon_{rg} = 0$, and $\Delta\varepsilon_{ig}$ has the same sign as $\Delta\varepsilon_{ic}$. All areas are participating in the correction scheme.

If $\vec{AF} = -\vec{AC}$, which means that $\Delta\varepsilon_{rg}$ completely cancells out $\Delta\varepsilon_{rc}$ and $\Delta\varepsilon_{ig} = 0$, then the operating point at $t=t_2$ is point B. Then, the actual time deviation correction is done by area i only even though the other areas are participating in the correction scheme. If area i is correcting more than its portion of system time deviation, this burden is



$$\vec{AB} = \begin{bmatrix} 1 \\ \frac{-Br}{6} \end{bmatrix} \cdot \Delta\varepsilon_{ic}\ , \quad \vec{AC} = \begin{bmatrix} 1 \\ \frac{Bi}{6} \end{bmatrix} \cdot \Delta\varepsilon_{rc}\ , \quad \vec{AD} = \vec{AB} + \vec{AC}$$

$$\vec{AC}' = \begin{bmatrix} 1 \\ \frac{Bi}{6} \end{bmatrix} \cdot \Delta\varepsilon'_{rc}\ , \quad \vec{AD}' = \vec{AB} + \vec{AC}'$$

$$\vec{BE} = \begin{bmatrix} 1 \\ \frac{-Br}{6} \end{bmatrix} \cdot \Delta\varepsilon_{ig}\ , \quad \vec{AF} = \begin{bmatrix} 1 \\ \frac{Bi}{6} \end{bmatrix} \cdot \Delta\varepsilon_{rg}$$

$$\vec{AG} = \vec{AB} + \vec{AC} + \vec{AF}$$

$$\vec{AH} = \vec{AB} + \vec{BE} + \vec{AC}' + \vec{AF}$$

$$\vec{AI} = \vec{AB} + \vec{BE} + \vec{AC}'$$

$$\vec{AJ} = \vec{AB} + \vec{BE} + \vec{AC}$$

Figure 4.10. The possible situations of the increase of inadvertent interchange of area i

also reflected as an increase of inadvertent interchange. Moreover, area i is responsible again for the reduction of increased inadvertent interchange.

Let us consider the time intervals $[t_1,t_2]$, $[t_2,t_3]$, $[t_3,t_4]\cdots$. If situations similar to those mentioned above are sustained for these time intervals, the inadvertent interchange of area i can be increased to an excessive amount. This is illustrated in Fig. 4.11. During the interval $[t_2,t_3]$, the effect of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$ should lie on the line BB', which is parallel to ε axis. Because the offset term for the corrective control is proportional to $\varepsilon(\tau)$ only among the variables $(\varepsilon(\tau), I_i(\tau))$, $I_i(\tau)$ can be continuously aggravated.

From the analysis presented above, the causes of accumulation of excessive inadvertent interchange energy can be summarized as:

(a) When some of the control areas do not participate in the system time deviation correction, and

(b) When the AGC control actions are superimposed on the corrective control actions in and outside area i during a given time period. Depending upon the sign and magnitude of the accumulated regulating deficiencies $\Delta\varepsilon_{ig}$ and $\Delta\varepsilon_{rg}$ caused by the control actions and the location of the initial operating point of an area i, the inadvertent interchange energy of area i can be increased (e.g., points G, H, I, and J of Fig. 4.10).

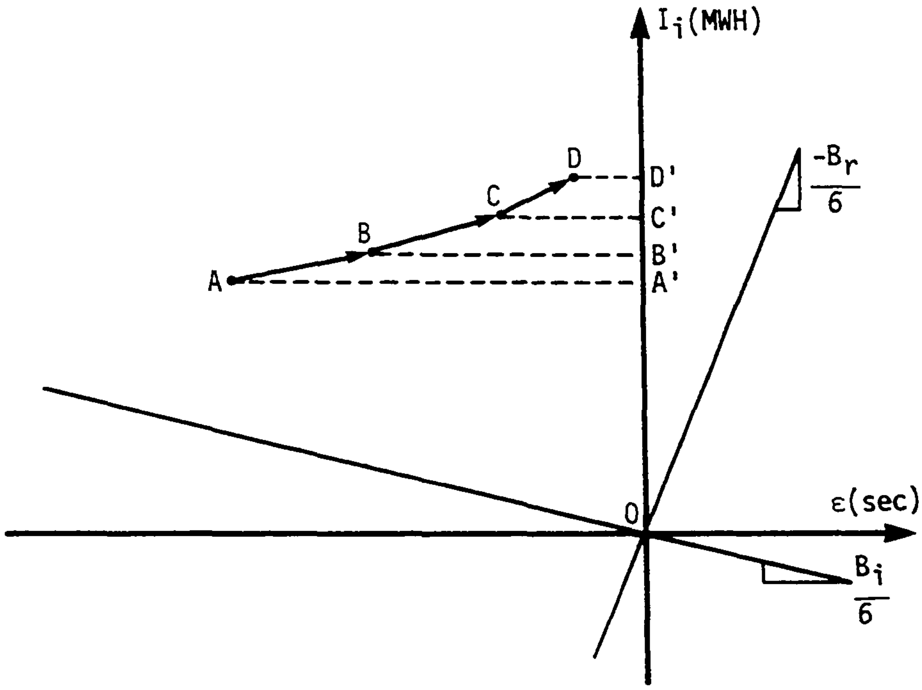


Figure 4.11. The increase of inadvertent interchange

V. STUDY OF ACCUMULATION OF INADVERTENT INTERCHANGE ENERGY

To investigate the causes of inadvertent interchange energy accumulation and the corrective control schemes to deal with it, a six-area interconnected power network is used. The system is similar to that described in Reference 28. Details of the system representation, modeling of the control devices, and simulation of the load disturbances are given in the Appendix.

The computer program used in this study is a modified version of the Automatic Generation Control Simulation Program developed by J. W. Lamont [28] of the Electric Power Research Institute (EPRI). Modification of the program (Version A) is implemented so as to include the correction term and error terms in the computation of the area control error.

A. A Single-Event Supplementary Control Simulator

The AGC simulation program is capable of studying three types of a single-event disturbance: (a) a step change in load; (b) a step change in generation without a change in generating capability; and (c) a step change in generation associated with a change in generating capability.

The basic assumptions are:

(a) All variables are equal to their schedule values before a disturbance occurs.

(b) After a disturbance, the governors do not operate until they have had the opportunity to receive a control signal.

(c) The control functions of governors and supplementary controllers are separated in time. The supplementary controllers do not operate until the governors have completed their initial responses.

(d) Generation change of an area due to control action is considered exponential after the governor and supplementary controller start to act.

(e) The power-frequency characteristic for each area is represented by three straight lines that are the natural generation, load, and combined governing characteristics.

(f) The maximum number of areas that can be represented by the simulation program is six. Each increment in time is set to 4 sec. The maximum number of time increments is 100.

B. Accumulation of Inadvertent Interchange Energy

The problem of excessive accumulation of inadvertent interchange energy is investigated in an interconnected power system made up of six control areas. The fundamental data for the six control area are given in Table 5.1. The area of interest is area 1.

Unless specifically stated, each area is assumed to participate in the system time deviation correction scheme and have no measurement or offset errors in frequency or net tie-line power. Similarly, there is no change of load or generation in each area unless it is mentioned.

Table 5.1. Fundamental data of each area[a]

			Governing		Regulator		Predisturbance Conditions			
Area	Governing Bias B_i MW/.1 Hz	Regulator Bias B_i MW/.1 Hz	Delay sec	Action sec	Delay sec	Action sec	Capability MW	Generation MW	Net Interchange MW	Load MW
1	-4	-4	4	16	28	52	1000	600	150	450
2	-8	-8	4	12	24	52	1000	500	-50	550
3	-5	-5	4	16	28	52	1000	400	-100	500
4	-5	-5	4	12	24	52	1000	450	50	400
5	-7	-7	4	16	28	48	1000	550	-50	600
6	-3	-3	4	12	28	52	800	200	0	200

[a]Scheduled frequency f_s = 60 Hz.

Six operating conditions are considered that can cause accumulation of the inadvertent interchange energy in area 1 during the continuous automatic time deviation correction period.

Case 1: Area 4, whose bias is about 15% of the system bias, does not participate in the time deviation correction (partial participation).

Case 2: There are frequency measurement or scheduling errors in areas 2 and 5, with $\phi_2 = -.1$ Hz and $\phi_5 = -.1$ Hz.

Case 3: There are tie-line power measurement or scheduling errors in areas 3 and 6, with $\tau_3 = -5.0$ MW and $\tau_6 = -3.0$ MW.

Case 4: There is a step load change in area 5 from 600 MW to 650 MW.

Case 5: There is a frequency measurement or scheduling error in the area of interest (area 1) with $\phi_1 = .1$ Hz.

Case 6: When the combination of all the above conditions exists: area 4 does not participate in the time error correction; with measurement or scheduling errors of $\phi_1 = .1$ Hz, $\phi_2 = -.1$ Hz, $\phi_5 = -.1$ Hz, $\tau_3 = -5.0$ MW, and $\tau_6 = -3.0$ MW; and a load change in area 5 from 600 MW to 650 MW.

Initial Conditions:

The initial operating condition at t=0 is given below:

$$\varepsilon(0) = -.179$$

$$I_1(0) = .119,\ I_2(0) = -.111,\ I_3(0) = -.064 \qquad (5.1)$$

$$I_4(0) = -.069,\ I_5(0) = -.091,\ I_6(0) = .217$$

The initial operating point of the area of interest (area) is on the line $I_1 = \frac{B_1}{6} \varepsilon$ (on the second quadrant of the (ε, I_1) plane). The time deviation component of area 1 (ε_1) is zero and the rest of the interconnection is wholly responsible for the time error and the inadvertent energy at $t=0$. This initial point is selected to demonstrate the following.

(a) Even though area 1 is not responsible at all for the initial time deviation, it is called upon to participate in the time deviation correction. A component of time deviation, due to its own corrective control, will be created at area 1.

(b) During the correction period, the inadvertent interchange energy of area 1 could increase further than its initial value for the six operating conditions.

Results:

The final values at t=248 sec obtained from the computer simulation results are shown in Table 5.2 for the above six cases. Figure 5.1 shows (ε, I_1) plot during the time interval [0,248] sec. Figure 5.2 shows (t, ε) and (t, I_1) plots during the same time interval. From these results, the following observations can be made:

1. In cases 1 and 4, in which no measurement or scheduling errors exist, while the system time deviation is corrected to zero, the inadvertent interchange energy for area 1 (I_1) is increased.
2. In cases 2, 3, 5 and 6, the system time deviation is corrected to nonzero equilibrium value; however, the inadvertent interchange energy for area 1 (I_1) continues to increase. Again, we

Table 5.2. The initial and final values of (ε, I_1)[a]

Case	Initial Values		Final Values	
	$I_1(0)$	$\varepsilon(0)$	$I_1(t_f)$	$\varepsilon(t_f)$
1	.119		.1373	0
2	.119		.2240	-.0282
3	.119	-.179	.1719	-.0151
4	.119		.1724	0
5	.119		.3174	.0074
6	.119		.6060	-.0423

[a] t_f = 248 sec.

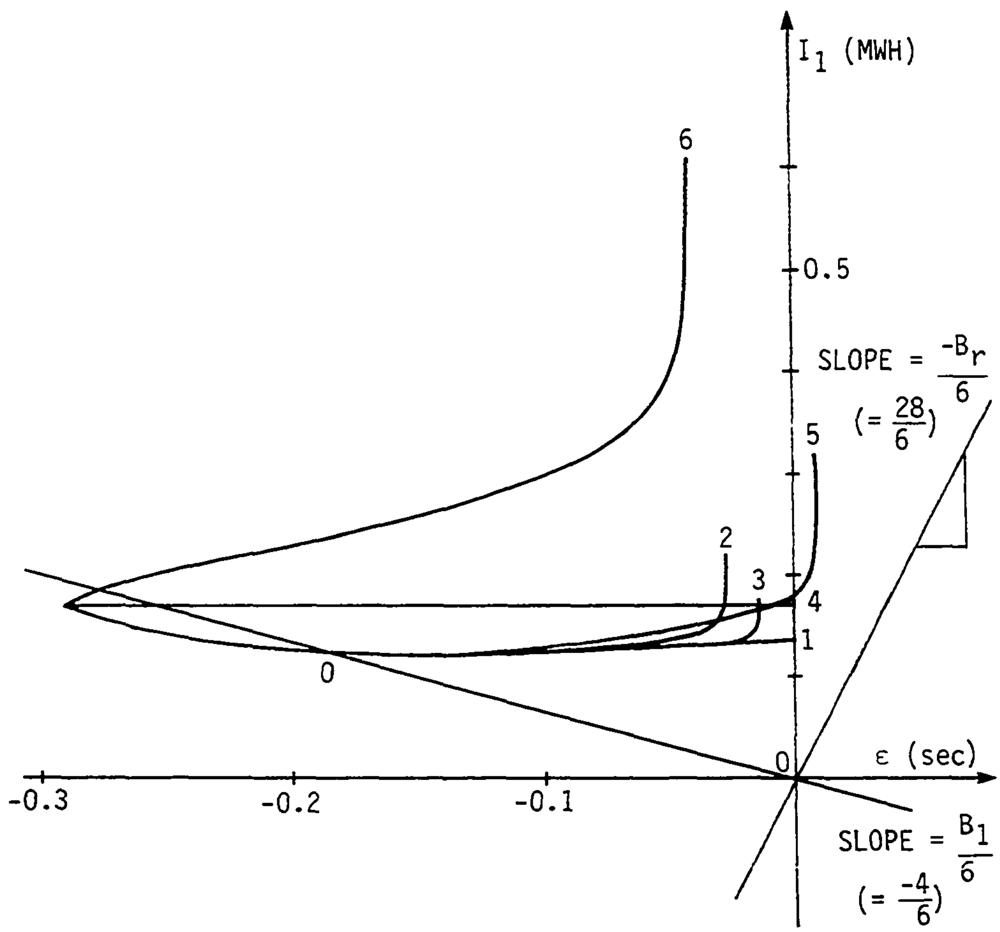


Figure 5.1. (ε, I_1) plot during [0, 248] seconds

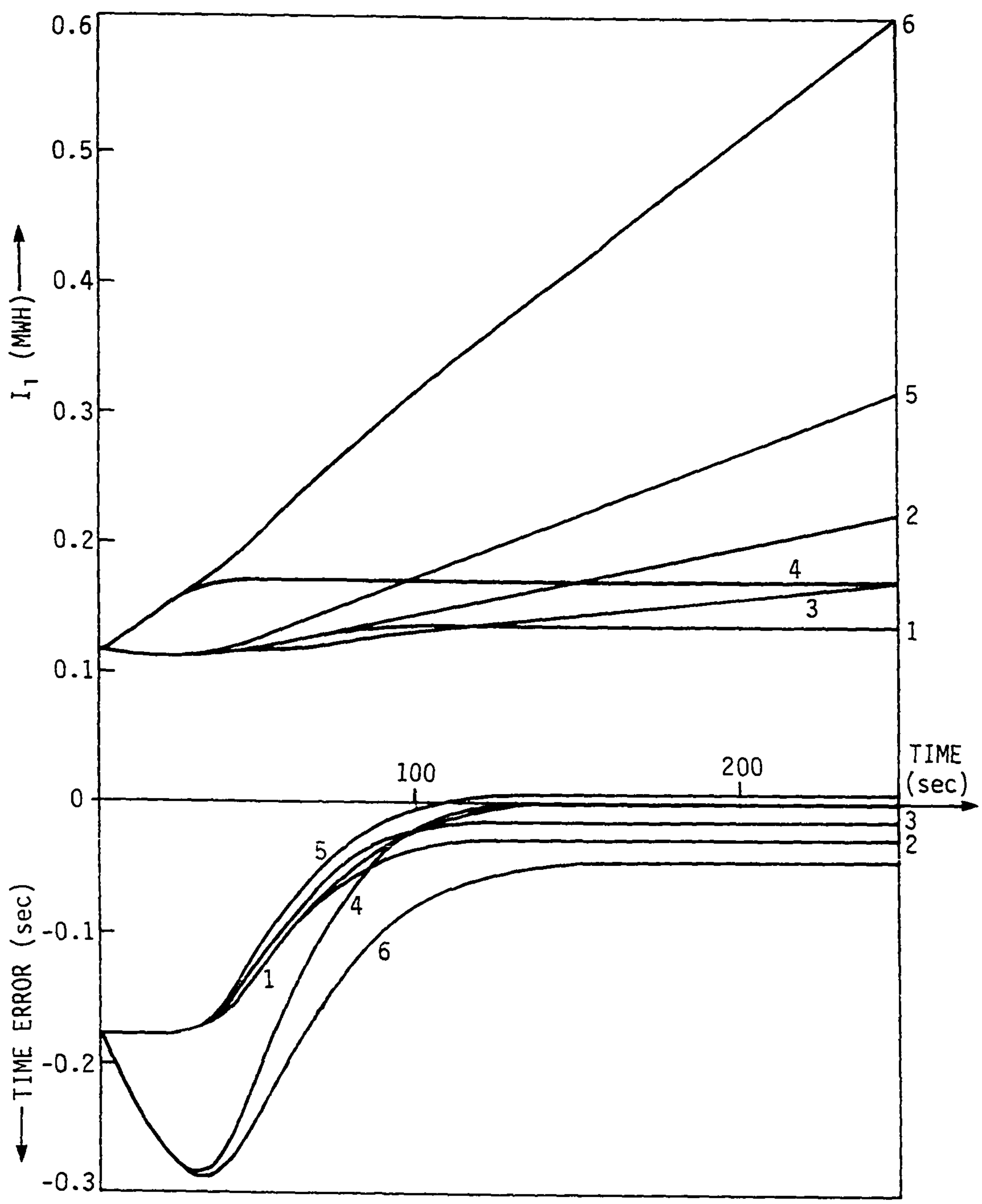


Figure 5.2. (t, ε(t)) and (t, I_1(t)) plots during [0, 248] seconds

note that measurement or scheduling errors in frequency or net tie-line powers exist for these cases. As expected, the most severe increase in inadvertent interchange energy occurs in case 6 because the operating condition is a combination of those of all other cases.

To explain the above results, let nonzero equilibrium value of the system time deviation be ε_q. Let the time period during which this equilibrium is maintained be $[\tau_1, \tau_2]$. For this period,

$$(\Delta\varepsilon_{1c} + \Delta\varepsilon_{1g}) = -(\Delta\varepsilon_{rc} + \Delta\varepsilon_{rg}) \tag{5.2}$$

where r denotes the rest of the interconnection for the area of interest, i.e., area 1.

This is illustrated in Fig. 5.3. $\vec{AB}$, $\vec{AD}$, $\vec{BC}$ and $\vec{AE}$ are the vector components due to $\Delta\varepsilon_{1c}$, $\Delta\varepsilon_{rc}$, $\Delta\varepsilon_{1g}$ and $\Delta\varepsilon_{rg}$, respectively. If the equality (Eq. 5.2) holds, the sum of these vector components is $\vec{AG}$. While the system time deviation is maintained at ε_q, I_1 continues to increase.

We note that due to $\Delta\varepsilon_{1g}$, area 1 is responsible for creating the vector component $\vec{BC}$. However, the vector component $\vec{AB}$, due to $\Delta\varepsilon_{1c}$, results from participating in the same time deviation correction scheme. When area 1 is correcting its inadvertent interchange energy unilaterally or bilaterally, this area should set $\Delta\varepsilon_{1c}$ such that it would produce an effect in the opposite direction of the vector component $\vec{AC}$. While it is reasonable to expect that area 1 be responsible for correcting $\vec{BC}$, it is to be noted that area 1 is also responsible for correcting $\vec{AB}$ resulted from participating in the system time deviation correction scheme.

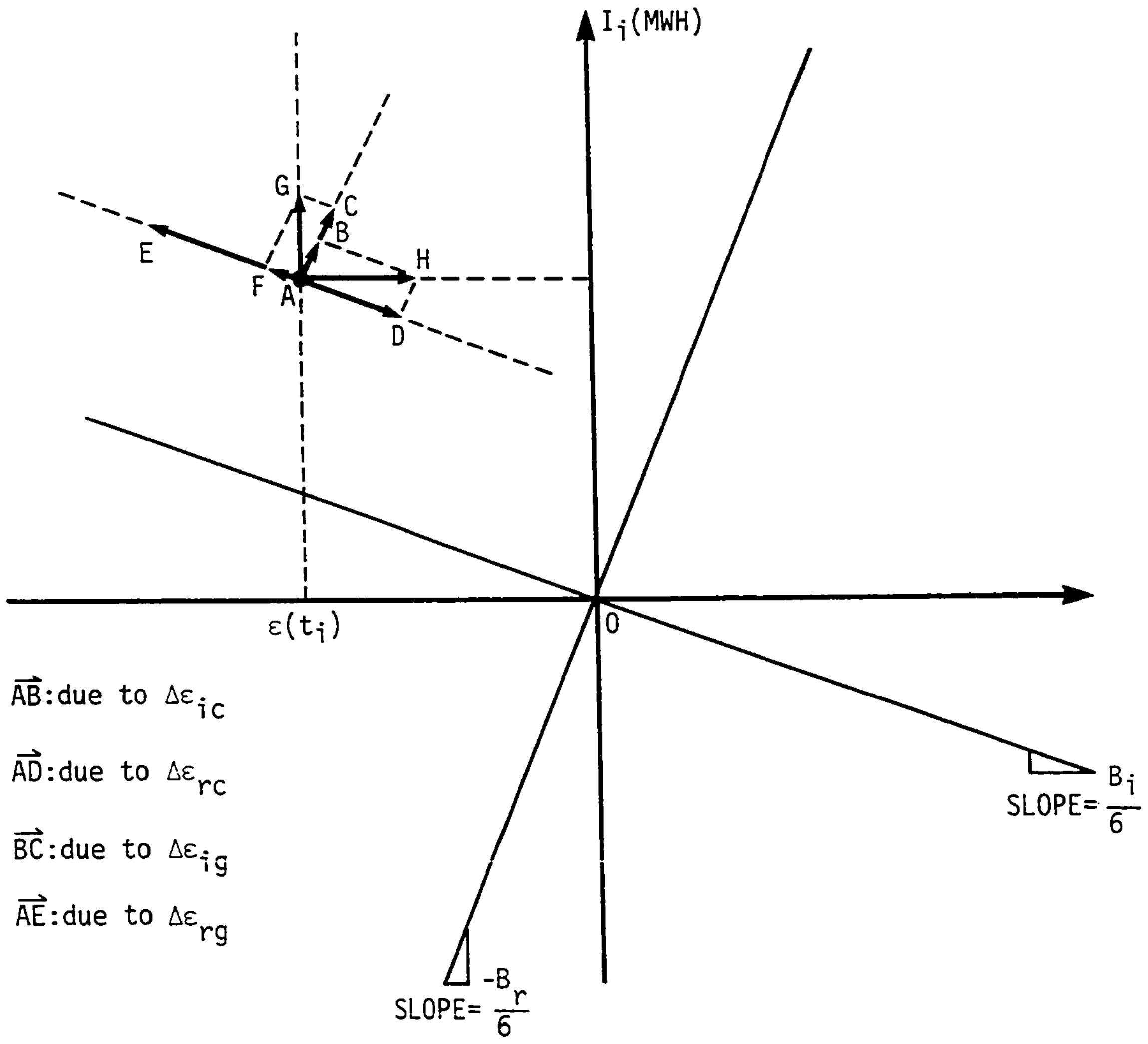


Figure 5.3. Increase of inadvertent interchange energy

C. Selective Participation in Time Deviation Correction

Since the initial conditions are selected such that area 1 is not responsible for the initial values of ε and I_1, the question is raised as to whether blocking the participation of that area in the correction of the system time deviation would reduce the accumulation of I_1. To demonstrate that effect, the participation of area 1 (in correcting the system time deviation) is blocked for the six cases outlined in Section B of this chapter.

The six new cases are analyzed by the AGC simulation program. Table 5.3 and Fig. 5.4 show the final operating conditions at t=248 sec and the (ε, I_1) plot in the time interval [0,248] sec.

Comparing the (ε, I_1) plot of Fig. 5.4 with that of Fig. 5.1, we note the following:

1. For the new cases 1, 2, and 3, where there is no accumulated regulating deficiencies $\Delta\varepsilon_{1g}$ caused by area 1, the final operating points at t=248 sec are located on the line $I_1 = \frac{B_1}{6}\ \varepsilon$. This results in significant reduction in the final values of inadvertent interchange I_1; however, the magnitudes of equilibrium system time deviation are slightly greater than those of Fig. 5.1. The system time deviation is the same as that obtained for a given period $[\tau_1, \tau_2]$ when

$$\Delta\varepsilon_{rc} = -\Delta\varepsilon_{rg} \tag{5.3}$$

2. For the new cases 5 and 6, where there is nonzero accumulated regulating deficiencies $\Delta\varepsilon_{1g}$ caused by area 1, the final values of the inadvertent interchange I_1 are increased. However, the

Table 5.3. The initial and final values of (ε, I_1)[a]

Case	Initial Values		Final Values	
	$I_1(0)$	$\varepsilon(0)$	$I_1(t_f)$	$\varepsilon(t_f)$
1	.119		0	0
2	.119		.0211	-.0321
3	.119	-.179	.0111	-.0171
4	.119		-.0280	0
5	.119		.2264	.0086
6	.119		.2379	-.0502

[a] t_f = 248 sec.

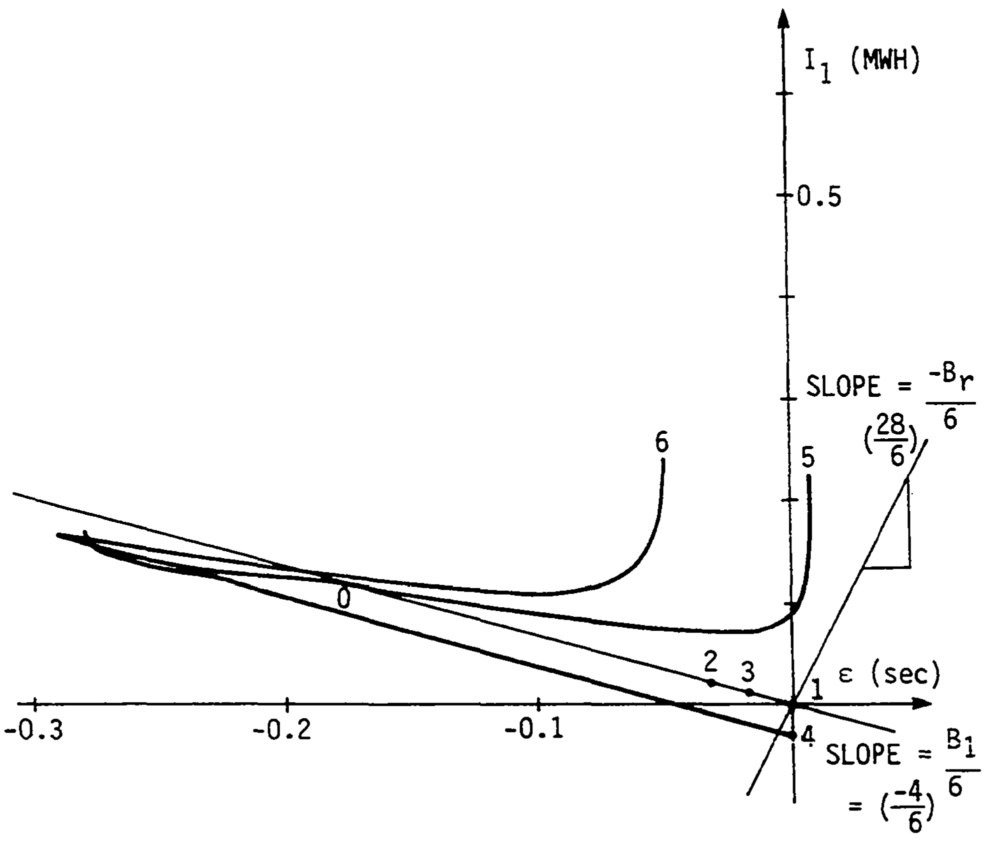


Figure 5.4. The effect of nonparticipation of area 1

increases in I_1 are significantly less than those shown in Fig. 5.1. In addition, the magnitude of the equilibrium system time deviations are slightly greater than those shown in Fig. 5.1. The system time deviation for a given period $[\tau_1, \tau_2]$ is the same as that obtained when

$$\Delta\varepsilon_{1g} = -(\Delta\varepsilon_{rc} + \Delta\varepsilon_{rg}) \tag{5.4}$$

3. For the new case 4 where there is a step change of load in area 5, the final system time deviation is returned to zero in both Figs. 5.1 and 5.4. The final value of I_1 is greater than the initial value shown in Fig. 5.1. However, I_1 goes to a negative value in Fig. 5.4.

As a summary, the inadvertent interchange energy of the area of interest (I_1) can increase depending upon the conditions of area 1 and the rest of the interconnection. However, area 1 controller is only responsible for creating a vector component due to its own $\Delta\varepsilon_{1g}$. It is not responsible for creating a vector component due to its own $\Delta\varepsilon_{1c}$ by participating in the system time deviation correction.

If this scheme is to be implemented, it should be remembered that nonparticipation of area 1 in the time deviation correction should be limited only to a period during which the operating points (ε, I_1) is in sectors 2-A or 4-A of the (ε, I_1) plane. Perhaps it can be generalized that any area i whose prevailing operating point is in sectors 2-A or 4-A should not participate in time deviation correction.

D. The Effect of Introducing a Frequency Offset in an Area

The effect of introducing a frequency offset to area 1 is investigated. The final operating point of the new case 6 of the previous section is considered as the initial operating point, i.e., at t=0, $(\varepsilon, I_1) = (-.0502, .2380)$.

It is assumed that in addition to area 1, area 4 (whose bias magnitude is approximately 15% of the total system bias) does not participate in the continuous automatic time deviation correction scheme. However, all other areas are participating in the scheme.

There are no frequency measurement or scheduling errors except in area 1 ($\phi_1 = -.1$ Hz). There are no load or generation changes in any of the areas. The (ε, I_1) plot during the time period [0,248] sec is shown in Fig. 5.5. The final operating point is given by $(\varepsilon, I_1) = (-.0105, -.0209)$.

Figure 5.6 shows a graphical analysis of this case. Both the system time deviation and inadvertent interchange energy I_1 are corrected. For any interval $[\tau_1, \tau_2] \varepsilon [0,248]$ sec, let the operating point P be $(\varepsilon(\tau_1), I_1(\tau_1))$. $\vec{PA}$ is a component caused by the introduced offset term ($\phi_1 = -.1$ Hz), and $\vec{PB}$ is a component caused by the correction terms of areas 2, 3, 5, and 6. The vector $\vec{PC}$ is a vector sum of $\vec{PA}$ and $\vec{PB}$, i.e., $\vec{PC} = \vec{PA} + \vec{PB}$.

Area 1 can reduce its inadvertent interchange further during the interval $[\tau_1, \tau_2]$. However, the correction of the system time deviation will be reduced.

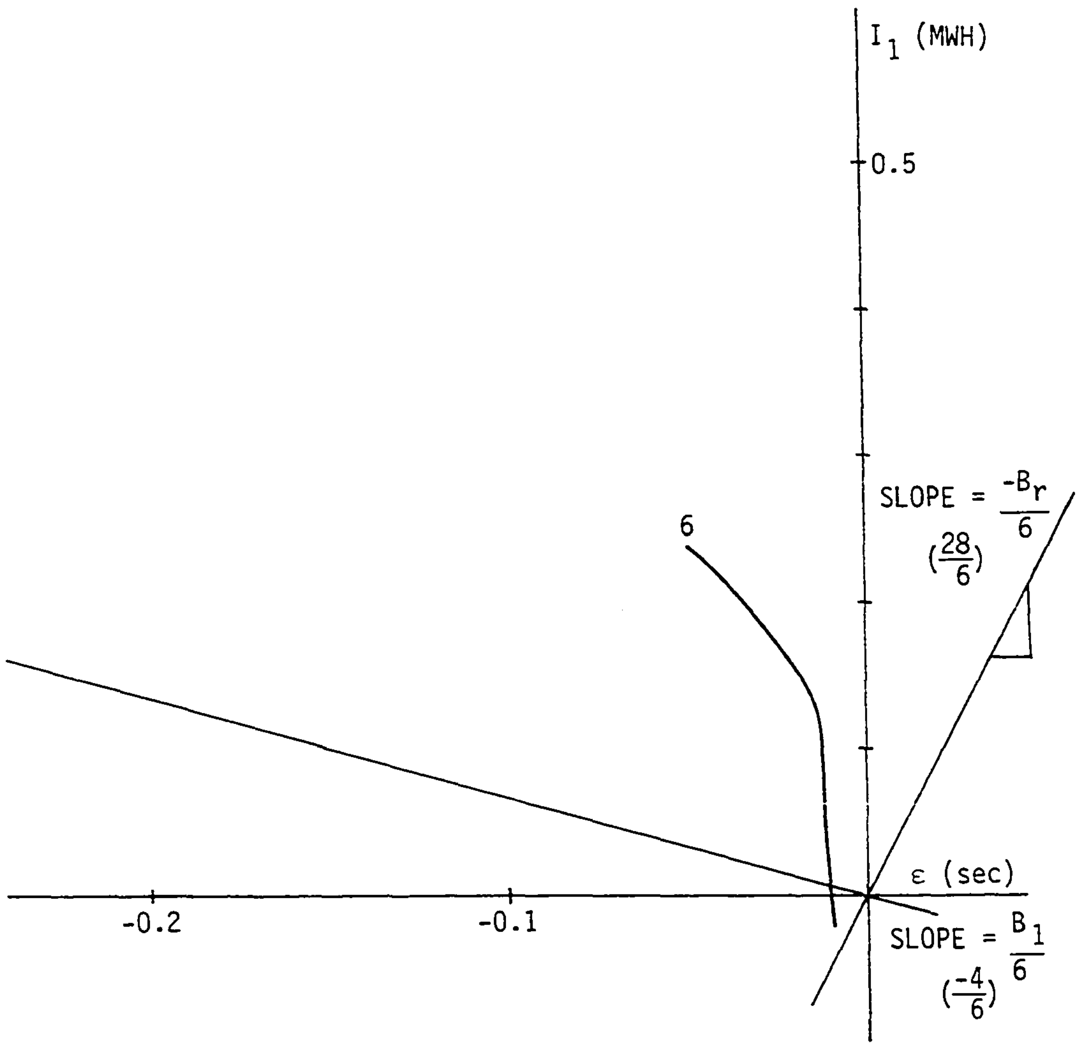


Figure 5.5. The effect of a frequency offset of area 1

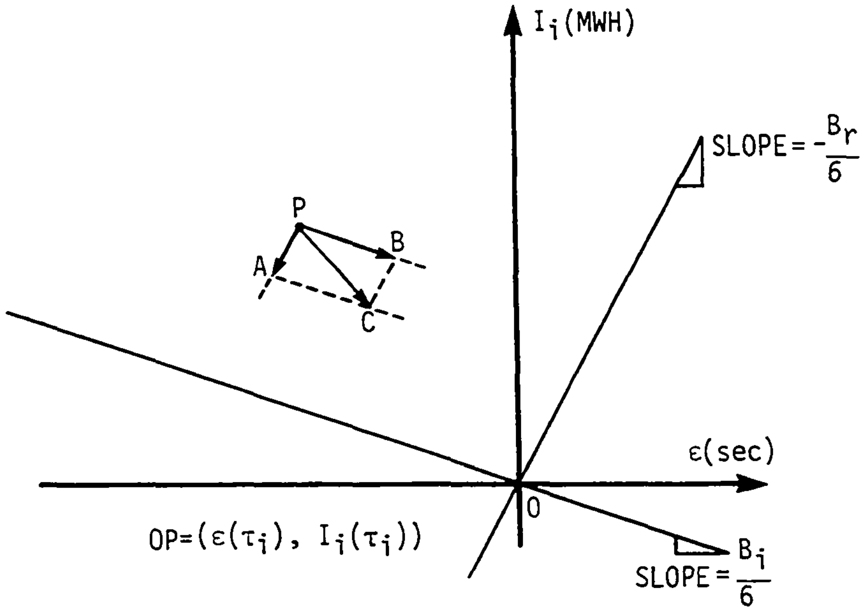


Figure 5.6. The graphical illustration of components

VI. THE DECOMPOSED COMPONENTS

In this chapter, analysis of the components of system time deviation and inadvertent interchange energy is presented. The decomposition of the signals into primary and secondary components is shown. Areas 1, 2, and 3 of Table 5.1 are considered as a three-area test system. The vector components caused by the AGC control actions and those caused by the corrective control actions are investigated.

A. The Component Caused by the AGC Control Actions

It is assumed that there are no corrective controls, no net tie-line power measurement or offset errors, and no load or generation changes in all areas. Table 6.1 shows six different conditions of the three areas. The accumulated regulating deficiencies by the AGC control action, $\Delta\varepsilon_{ig}$ and $\Delta\varepsilon_{rg}$, are generated by assuming constant frequency measurement or offset errors. The frequency measurement or offset errors of areas 2 and 3 are identical for cases B, C, D, E, and F in Table 6.1.

The initial operating points of all areas are assumed to be at their origins. The final values of the operating points at t=184 sec for the same six cases are given in Table 6.2. Figures 6.1, 6.2, and 6.3 show the values of (ε, I_i) for i=1,2,3 at t=184 sec, respectively.

From the results obtained, the following observations are made.

1. Area 1

The final operating points, B, C, D, E, and F, are located on a line parallel to the $I_1 = -\frac{B_2+B_3}{6}\varepsilon$ line. These points have the same second-

Table 6.1. Frequency measurement error in each area

Area	A	B	C	D	E	F
1	-.3	-.3	-.2	-.1	0	.2
2	-.2	-.2	-.2	-.2	-.2	-.2
3	-.2	-.1	-.1	-.1	-.1	-.1

Table 6.2. Conditions at t=184 sec

Cases	A	B	C	D	E	F
f(Hz)	59.78	59.81	59.83	59.85	59.88	59.92
$\Delta\varepsilon$(sec)	-.542	-.471	-.414	-.357	-.300	-.186
ΔI_1(MWH)	-.123	-.171	-.047	.076	.200	.447
ΔI_2(MWH)	.076	-.019	-.095	-.171	-.247	-.399
ΔI_3(MWH)	.048	.190	.143	.095	.048	-.047

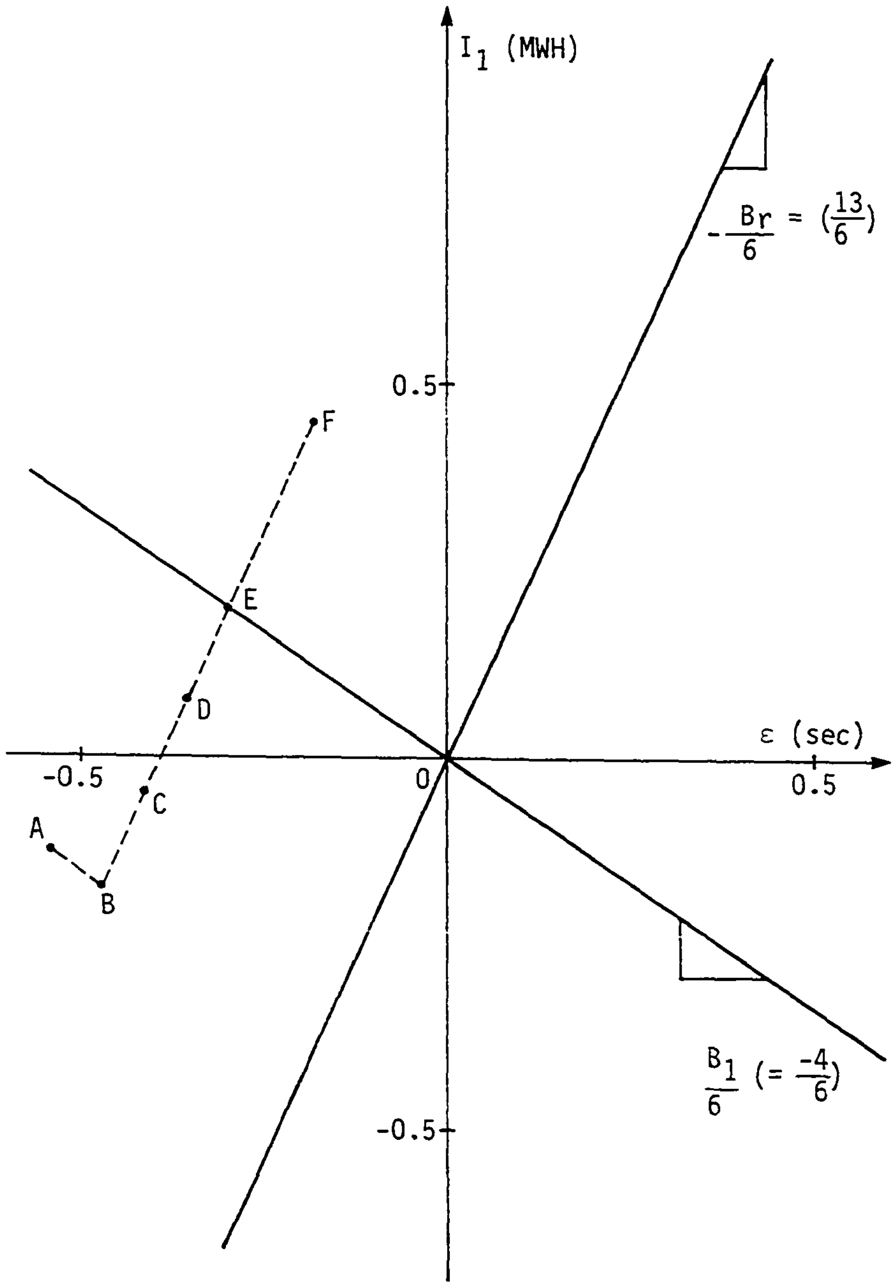


Figure 6.1. Area 1 (t = 184 sec)

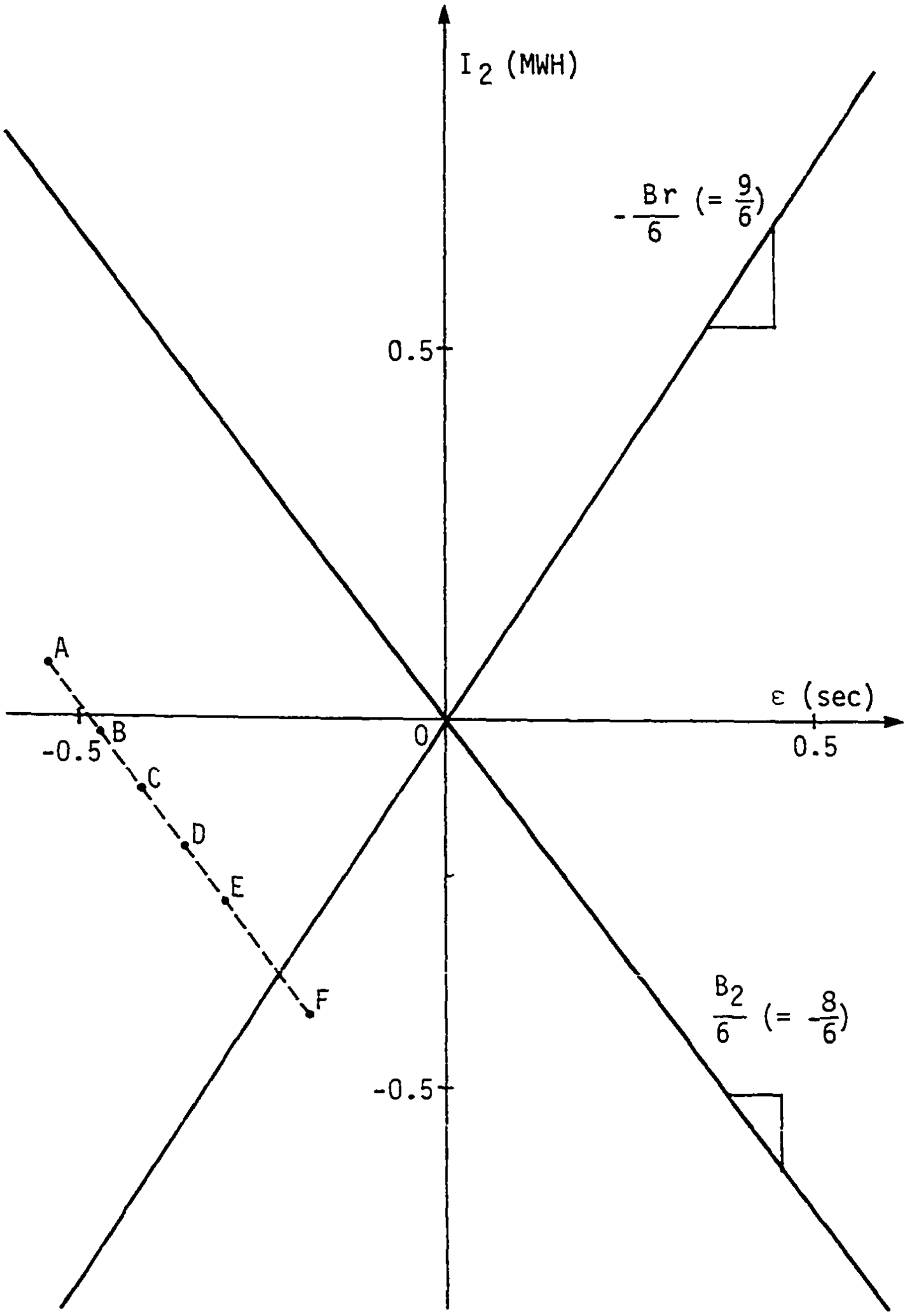


Figure 6.2. Area 2 (t = 184 sec)

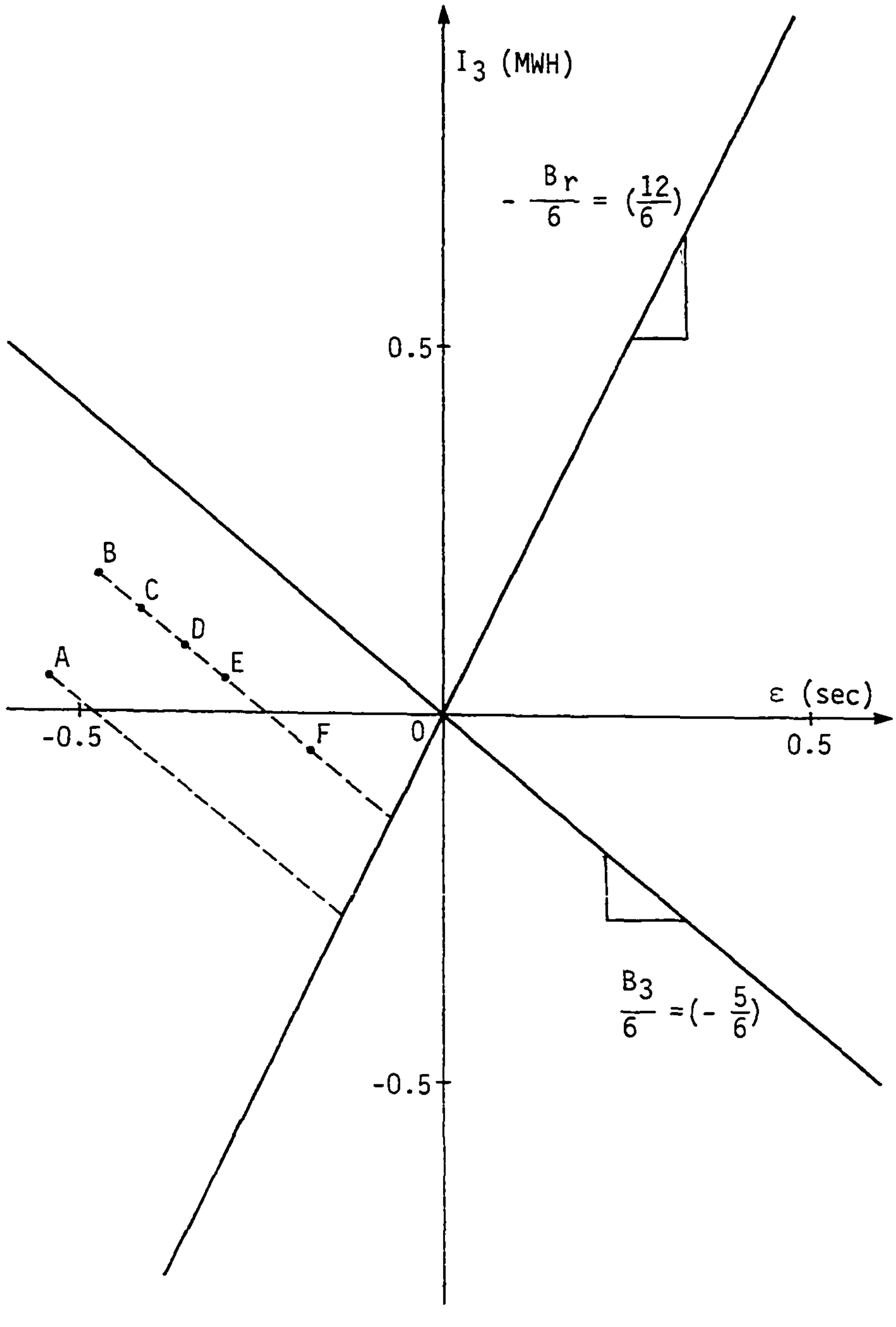


Figure 6.3. Area 3 (t = 184 sec)

ary vector component $\begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \varepsilon_r$ caused by areas 2 and 3. When there is no accumulated regulating deficiencies $\Delta\varepsilon_{1g}$ in area 1 (Case E), the point E is on the line $I_1 = \frac{B_1}{6} \varepsilon$ (Fig. 6.1). The final operating point A is on a vector that is that is the sum of the vectors $\vec{OB}$ and $\vec{BA}$. The vector $\vec{BA}$ is parallel to the line $I_1 = \frac{B_1}{6} \varepsilon$.

2. Area 2

Area 2 has the same operating conditions for all the cases (ϕ_2 = -.2 Hz in Table 6.1). In other words, the accumulated regulating deficiencies $\Delta\varepsilon_{2g}$ are the same for all the cases. All final operating points are on a line parallel to the $I_2 = \frac{B_2}{6} \varepsilon$ line (Fig. 6.2).

3. Area 3

All the operating conditions for area 3 are the same except for Case A. The final operating points, except A, are on a line parallel to the $I_3 = \frac{B_3}{6} \varepsilon$ line. The vector $\vec{OA}$ is the vector sum of $\vec{OB}$ and $\vec{BA}$. The vector $\vec{BA}$ is parallel to the line $I_3 = -\frac{B_1+B_2}{6} \varepsilon$.

The above observations are summarized as follows.

(a) The vector component caused by area i itself is on the $I_i = -\frac{B_r}{6} \varepsilon$ line and can be represented as $\begin{bmatrix} 1 \\ \frac{B_r}{6} \end{bmatrix} \cdot (\Delta\varepsilon_{ig})$.

(b) The vector component caused by area r is on the $I_i = \frac{B_i}{6} \varepsilon$ line and can be represented as $\begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (\Delta\varepsilon_{rg})$.

(c) The vector sum of these two is a vector that represents the system time deviation and inadvertent interchange energy.

These examples show the cases where the final system time deviation is negative. Depending on the operating conditions of areas, the final operating points can be in any of the sectors of 2-A, 2-B, 3-A, or 3-B of the (ε, I_i) plane from Fig. 6.1-6.3.

B. The Component Caused by the Corrective Control Actions

In this section, the components caused by the accumulated regulating deficiencies caused by the corrective control action, $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{rc}$, are investigated. Table 6.3 shows the initial conditions of the system time deviation and inadvertent interchanges of the three-area test system. Seven different cases are studied using the AGC simulator program (Table 6.4). It is assumed that there are no frequency measurement or offset errors, no tie-line power measurement or offset errors, and no load or generation changes except for Case M in Table 6.4. In Case M, it is assumed that area 2 load is increased from 550 MW to 650 MW at t=0.

It is also assumed that only correction areas as shown in Table 6.4 reduce their area component of system time deviation to zero in order to investigate the new corrective control scheme suggested by Cohn. The final operating conditions at t=192 sec are also shown in Table 6.4. The final operating points are shown in Figs. 6.4-6.6 for i=1,2,3, respectively. From these results, we can make the following observations.

1. Area 1

Area 1 returns its own area component of system time deviation to zero in cases G, J, K, L, and M when it is the assigned area for correction (Fig. 6.4). When other area are assigned for correction (Cases H, I), the final points H and I are on a line parallel to the line $I_1 = \frac{B_1}{6}\varepsilon$.

Table 6.3. Initial conditions

Initial values	Area 1	Area 2	Area 3	Total
I_i(MWH)	1.0	-1.0	0	0
ε_i(sec)	.5882	.1176	.2941	1.0

Table 6.4. The effect of time error component correction

Case No.	Correction Area	Final Values			
		$I_1(t_f)$	$I_2(t_f)$	$I_3(t_f)$	$\varepsilon(t_f)$
G	1	-.276	-.214	.491	.411
H	2	1.079	-1.176	.098	.882
I	3	1.196	-.607	-.589	.705
J	1,2	-.198	-.391	.589	.293
K	1,3	-.080	.178	-.098	.116
L	1,2,3	-.001	.002	0	-.001
M[a]	1	.015	-.739	.724	-.026

[a]Area 2 load is increased from 550 MW to 650 MW at t=0.

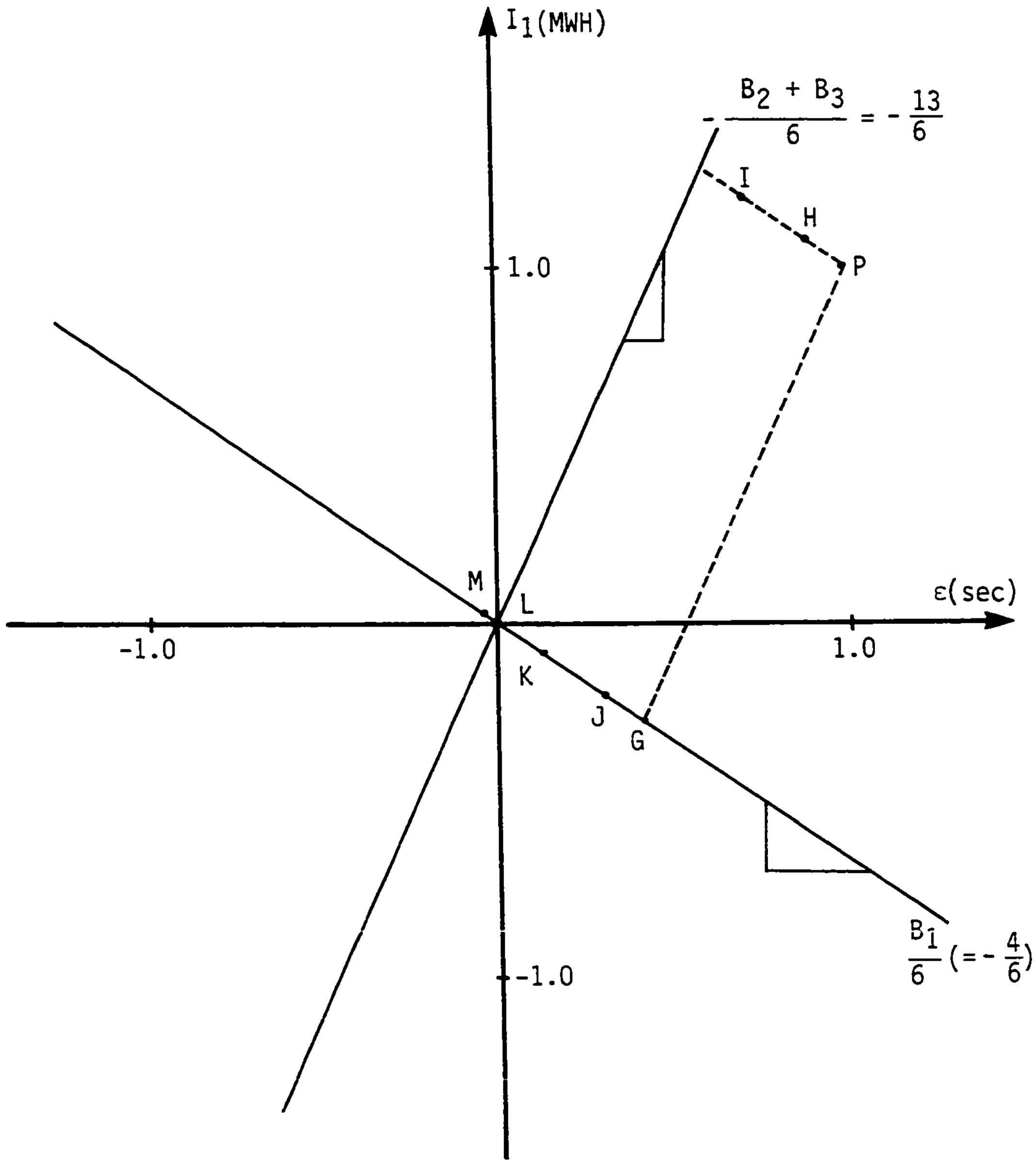


Figure 6.4. The effect of $\Delta\varepsilon_{ic}$ and $\Delta\varepsilon_{r(1)c}$ on area 1

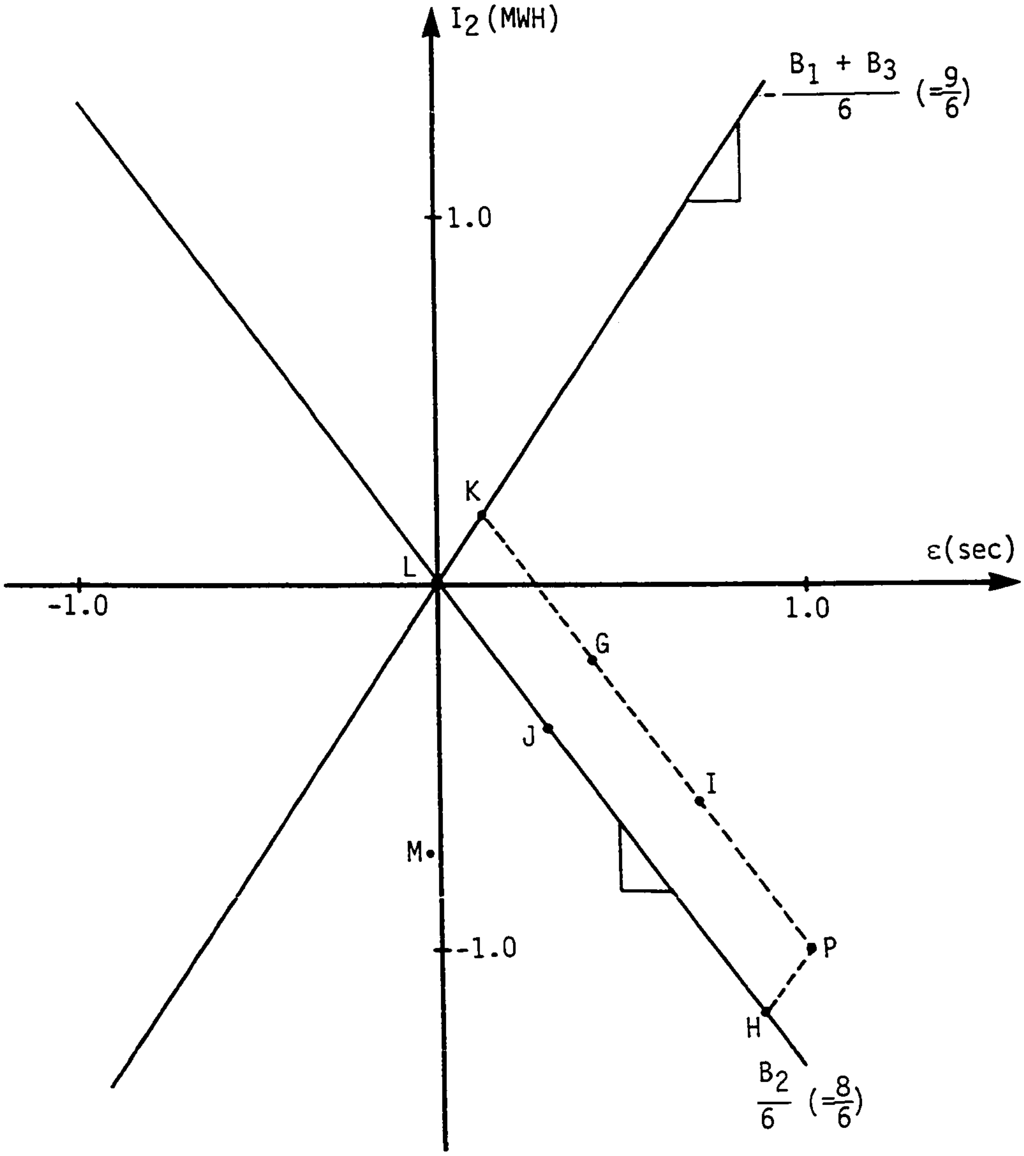


Figure 6.5. The effect of $\Delta\varepsilon_{2c}$ and $\Delta\varepsilon_{\gamma(2)c}$ on area 2

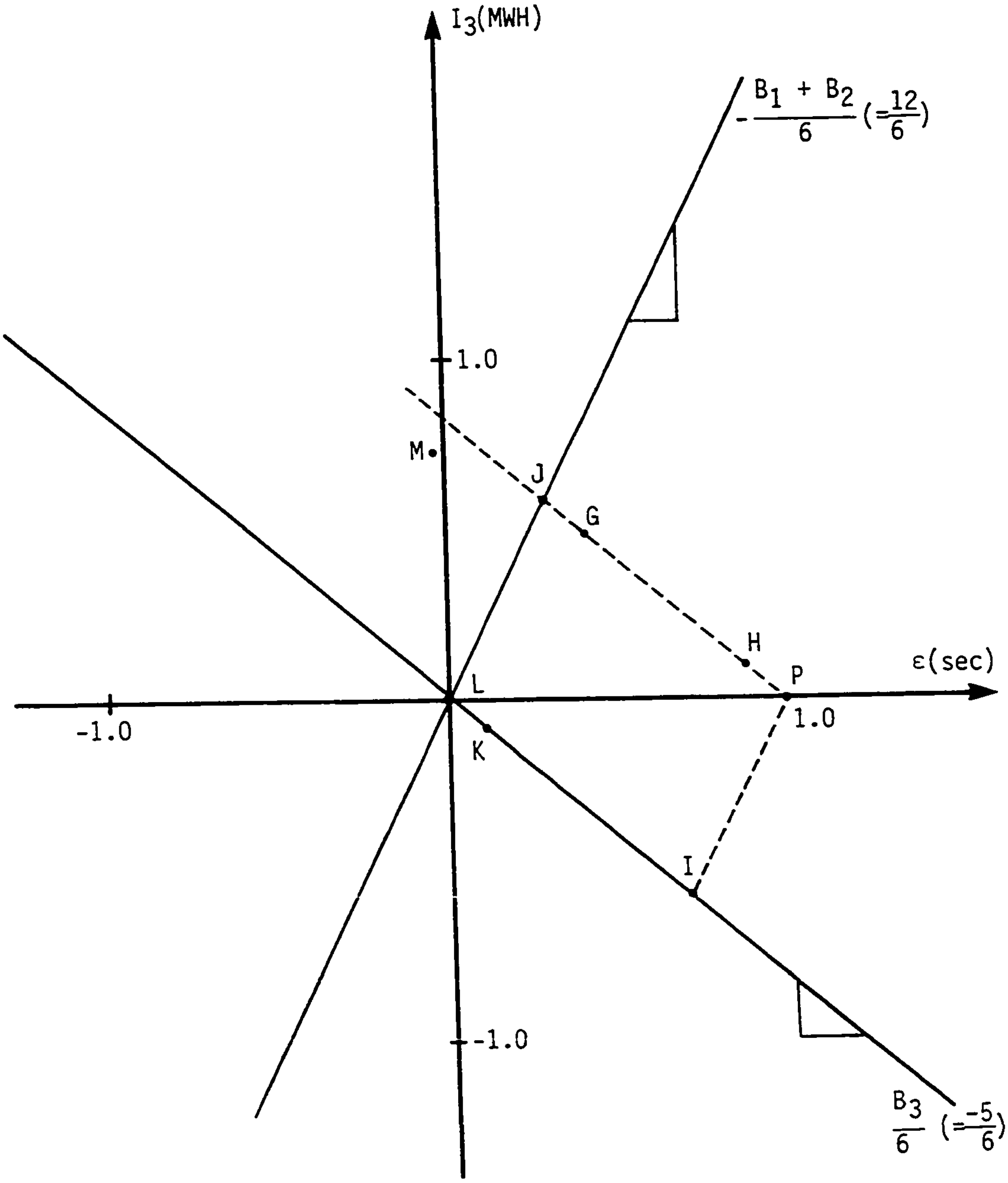


Figure 6.6. The effect of $\Delta\varepsilon_{3c}$ and $\Delta\varepsilon_{\gamma(3)c}$ on area 3

Case J: $\vec{PJ} = \vec{PG} + \vec{PH}$ (Case G and Case H).

Case K: $\vec{PK} = \vec{PG} + \vec{PI}$ (Case G and Case I).

Case L: $\vec{PL} = \vec{PG} + \vec{PH} + \vec{PI}$ (Cases G, H, and I).

2. Area 2

Area 2 returns its own area component of system time deviation to zero in Cases J, K, and L when it is the area assigned for correction (Fig. 6.5). When other areas are assigned for correction (Cases G, I, and K), the final points G, I, and K are on a line parallel to the line $I_2 = \frac{B_2}{6}\varepsilon$.

Case J: $\vec{PH} + \vec{PG}$ (Case H and Case G).

Case L: $\vec{PH} + \vec{PG} + \vec{PI}$ (Cases H, G, and I).

3. Area 3

Area 3 returns its own area component of system time deviation to zero in Cases I, K, and L when it is the area assigned for correction (Fig. 6.6). When other areas are assigned for correction (Cases G, H, and J), the final points are on a line parallel to the line $I_3 = \frac{B_3}{6}\varepsilon$.

Case K: $\vec{PI} + \vec{PG}$ (Case I and Case G).

Case L: $\vec{PI} + \vec{PG} + \vec{PH}$ (Cases I, G, and H).

As a summary, the vector component caused by the accumulated regulating deficiencies $\Delta\varepsilon_{ic}$ by the corrective control action in area i is located on a line parallel to the line $I_i = \frac{-B_r}{6}\varepsilon$ and, hence, can be represented as $\begin{bmatrix} 1 \\ \frac{-B_r}{6} \end{bmatrix} \cdot (\Delta\varepsilon_{ic})$. The vector component caused by the accumulated regulating deficiencies $\Delta\varepsilon_{rg}$ by the corrective control action in area r is located on a line parallel to the line $I_i = \frac{B_i}{6}\varepsilon$ and, hence, can be represented as $\begin{bmatrix} 1 \\ \frac{B_i}{6} \end{bmatrix} \cdot (\Delta\varepsilon_{rc})$.

4. Case M

Case M has the same operating condition as Case G except that there is a load change in area 2 from 550 MW to 650 MW at t=0. In both cases, only area 1 is assigned to correct its own area component of system time deviation. Figure 6.4 shows that area 1 can return its own component of system time deviation to zero when this area is assigned to correct its area component of system time deviation continuously and automatically. However, for areas 2 and 3 where corrective action is not assigned, the final operating points M are located, as shown in Figs. 6.5 and 6.6. These can be explained as follows.

From Eq. 2.9,

$$\Delta\varepsilon_1 = \left(-\frac{6}{B_s}\right)\left[\int_{t_1}^{t_2}(ACE_1 + \tau_1 - 10B_1\phi_1)dt + \int_{t_1}^{t_2}(CORR)_1 dt\right] \quad (6.1a)$$

$$\Delta\varepsilon_2 = \left(-\frac{6}{B_s}\right)\left[\int_{t_1}^{t_2}(ACE_2 + \tau_2 - 10B_2\phi_2)dt + \int_{t_1}^{t_2}(CORR)_2 dt\right] \quad (6.1b)$$

$$\Delta\varepsilon_3 = \left(-\frac{6}{B_s}\right)\left[\int_{t_1}^{t_2}(ACE_3 + \tau_3 - 10B_3\phi_3)dt + \int_{t_1}^{t_2}(CORR)_3 dt\right] \quad (6.3c)$$

Let t_1' be the time such that all the governors complete their actions but before the supplementary regulators start their actions, after a sudden load change in area 2 at $t=t_1$. From the assumptions, all τ,ϕ terms are zero. Equation 6.1 can be written as

$$\Delta\varepsilon_1 = \left(-\frac{6}{B_s}\right)\left[\int_{t_1}^{t_1'}(ACE_1)dt + \int_{t_1}^{t_1'}(CORR)_1 dt\right]$$

$$+ \left(-\frac{6}{B_s}\right)\left[\int_{t_1'}^{t_2}(ACE_1)dt + \int_{t_1'}^{t_2}(CORR)_1 dt\right] \quad (6.2a)$$

$$\Delta\varepsilon_2 = \left(- \frac{6}{B_s} \right) \left[\int_{t_1}^{t_1'} (ACE_2)dt + \int_{t_1}^{t_1'} (CORR)_2 dt \right]$$

$$+ \left(- \frac{6}{B_s} \right) \left[\int_{t_1'}^{t_2} (ACE_2)dt + \int_{t_1'}^{t_2} (CORR)_2 dt \right] \qquad (6.2b)$$

$$\Delta\varepsilon_3 = \left(- \frac{6}{B_s} \right) \left[\int_{t_1}^{t_1'} (ACE_3)dt + \int_{t_1}^{t_1'} (CORR)_3 dt \right]$$

$$+ \left(- \frac{6}{B_s} \right) \left[\int_{t_1'}^{t_2} (ACE_3)dt + \int_{t_1'}^{t_2} (CORR)_3 dt \right] \qquad (6.2c)$$

During $[t_1, t_1']$,

$$\int_{t_1}^{t_1'} (CORR)_i dt = 0 \qquad i = 1,2,3 \qquad (6.3)$$

During $[t_1', t_2]$,

$$\int_{t_1'}^{t_2} (ACE)_i dt = 0 \qquad i = 1,3 \qquad (6.4a)$$

$$\int_{t_1'}^{t_2} (ACE)_2 dt \neq 0 \qquad (6.4b)$$

$$\int_{t_1'}^{t_2} (CORR)_i dt = 0 \qquad i = 2,3 \qquad (6.4c)$$

Equation 6.2 can be written as

$$\Delta\varepsilon_1 = \left(- \frac{6}{B_s} \right) \int_{t_1}^{t_1'} (ACE_1)dt + \left(- \frac{6}{B_s} \right) \int_{t_1'}^{t_2} (CORR)_1 dt \qquad (6.5a)$$

$$\Delta\varepsilon_2 = \left(-\frac{6}{B_s} \right) \int_{t_1}^{t_1'} (ACE_2)dt + \left(-\frac{6}{B_s} \right) \int_{t_1'}^{t_2} (ACE_2)dt \qquad (6.5b)$$

$$\Delta\varepsilon_3 = \left(-\frac{6}{B_s} \right) \int_{t_1}^{t_1'} (ACE_3)dt \qquad (6.5c)$$

It is the basic assumption that the supplementary regulator does not respond during governing action period $[t_1, t_1']$. Even though ACE_1 and ACE_3 are not zero during the period, supplementary regulators do not respond at all. The effects shown in Eq. 6.5b and 6.5c are reflected as the final point M in Figs. 6.5 and 6.6.

VII. DEBIT/CREDIT SYSTEM

A. Introduction

When area i knows its operating point (ε, I_i), this area can determine its area component of system time deviation ε_i. Once ε_i is determined (from Eq. 3.9), $(-\frac{B_s}{6}) \cdot \varepsilon_i$ is the accumulated regulating deficiencies (MWH) of area i. For Q control areas in the interconnection, there are Q accumulated regulating deficiencies (MWH). The factor $(-\frac{B_s}{6})$ is common for all areas. The area component of system time deviation ε_i is just the accumulated regulating deficiencies (MWH) of area i divided by the common factor $(-\frac{B_s}{6})$.

Let $\varepsilon_1(t_1)$, $\varepsilon_2(t_1), \cdots$, and $\varepsilon_Q(t_1)$ be the area component of system time deviation at time t_1 for areas $1, 2, \cdots$, and Q, respectively. The sum of all the area components of time deviation is the system time deviation $\varepsilon(t_1)$. However, some of these components may have positive values while others may have negative values. The sum of the absolute values of these is $\sum_{i=1}^{Q} |\varepsilon_i(t_1)|$. Then,

$$\sum_{i=1}^{Q} |\varepsilon_i(t_1)| \geq \left| \sum_{i=1}^{Q} \varepsilon_i(t_1) \right| = |\varepsilon(t_1)| \tag{7.1}$$

To return the initial system time deviation $\varepsilon(t_1)$ to zero, an amount of regulation of $(-\frac{B_s}{6}) \cdot |\varepsilon(t_1)|$ (MWH) is necessary. Let $\varepsilon_p(t_1)$ be the sum of positive area components (of ε_i) and $\varepsilon_N(t_1)$ be the sum of negative area components (of ε_i).

$$\varepsilon(t_1) = \varepsilon_p(t_1) + \varepsilon_N(t_1) \tag{7.2}$$

Let $\varepsilon_{P1}(t_1)$, $\varepsilon_{P2}(t_1),\cdots$, $\varepsilon_{PK}(t_1)$ be the positive area components of ε_i and B_{P1}, $B_{P2},\cdots$, B_{PK} be the corresponding area bias. Let $\varepsilon_{N1}(t_1)$, $\varepsilon_{N2}(t_1),\cdots$, $\varepsilon_{N\ell}(t_1)$ be the negative area components of ε_i and B_{N1}, $B_{N2},\cdots$, $B_{N\ell}$ be the corresponding area bias.

$$\varepsilon_P(t_1) = \sum_{i=1}^{K} \varepsilon_{Pi}(t_1) \tag{7.3a}$$

$$\varepsilon_N(t_1) = \sum_{j=1}^{\ell} \varepsilon_{Nj}(t_1) \tag{7.3b}$$

where $K + \ell = Q$.

At $t=t_2$,

$$\sum_{i=1}^{Q} |\varepsilon_i(t_2)| = \sum_{i=1}^{Q} |\varepsilon_i(t_1) + \Delta\varepsilon_i| \tag{7.4a}$$

$$= |\varepsilon_{P1}(t_1) + \Delta\varepsilon_{P1}|+|\varepsilon_{P2}(t_1) + \Delta\varepsilon_{P2}|+\cdots+|\varepsilon_{PK}(t_1)+\Delta\varepsilon_{PK}|$$

$$+|\varepsilon_{N1}(t_1)+\Delta\varepsilon_{N1}|+|\varepsilon_{N2}(t_1)+\Delta\varepsilon_{N2}|+\cdots+|\varepsilon_{N\ell}(t_1)+\Delta\varepsilon_{N\ell}| \tag{7.4b}$$

We will consider the situations where $\varepsilon(t_1)\gtreqless 0$.

a) When $\varepsilon(t_1)<0$, let

$$\Delta\varepsilon_{Pi} = -\varepsilon_{Pi}(t_1) \qquad i=1,2,\cdots,K \tag{7.5}$$

$$\sum_{i=1}^{K} \Delta\varepsilon_{Pi} = -\varepsilon_P(t_1) \tag{7.6}$$

$$\text{Set } \sum_{j=1}^{\ell} \Delta\varepsilon_{Nj} = \varepsilon_P(t_1) \text{ where } \Delta\varepsilon_{Nj}\geq 0 \tag{7.7}$$

$$\sum_{i=1}^{Q}|\varepsilon_i(t_2)|=|\varepsilon_{P1}(t_1)-\varepsilon_{P1}(t_1)|+|\varepsilon_{P2}(t_1)-\varepsilon_{P2}(t_1)|+\cdots+|\varepsilon_{PK}(t_1)-$$

$$\varepsilon_{PK}(t_1)\Big| + \sum_{j=1}^{\ell} \left|\varepsilon_{Nj}(t_1)+\Delta\varepsilon_{Nj}\right| \tag{7.8}$$

Equation 7.8 implies that areas with positive area components reduce their respective area component to zero at $t=t_2$.

For any area i with positive area component,

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_{Pi} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -\frac{B_s-B_{Pi}}{6} & \frac{B_{Pi}}{6} \end{bmatrix} \begin{bmatrix} -\varepsilon_{Pi}(t_1) \\ -\varepsilon_P(t_1)+\varepsilon_{Pi}(t_1)+\varepsilon_P(t_1) \end{bmatrix} = \begin{bmatrix} 0 \\ (-\frac{B_s}{6})\cdot(-\varepsilon_{Pi}(t_1)) \end{bmatrix} \tag{7.9}$$

For any area j with negative area component,

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_{Nj} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -\frac{B_s-B_{Nj}}{6} & \frac{B_{Nj}}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{Nj} \\ -\varepsilon_P(T_1)+\varepsilon_P(t_1)-\Delta\varepsilon_{Nj} \end{bmatrix} = \begin{bmatrix} 0 \\ (\frac{-B_s}{6})\cdot\Delta\varepsilon_{Nj} \end{bmatrix} \tag{7.10}$$

Once Eqs. 7.9 and 7.10 hold, the areas with positive area components of ε_i reduce their respective area component of ε_i to zero and, hence, become not responsible for creating accumulated regulating deficiencies. Areas with negative area components of ε_j also reduce their respective component of ε_j and become less responsible for creating accumulated regulating deficiencies. From Eqs. 7.9 and 7.10, there is no change in the system time deviation, but only changes in inadvertent interchanges will occur.

b) When $\varepsilon(t_1) \geq 0$, let

$$\Delta\varepsilon_{Nj} = -\varepsilon_{Nj}(t_1) \qquad j=1,2,\cdots,\ell \tag{7.11}$$

$$\sum_{j=1}^{\ell} \Sigma\varepsilon_{Nj} = -\varepsilon_N(t_1) \tag{7.12}$$

Set

$$\sum_{i=1}^{K} \Delta\varepsilon_{Pi} = \varepsilon_N(t_1) \text{ where } \Delta\varepsilon_{Pi} \leq 0. \tag{7.13}$$

$$\sum_{i=1}^{Q} |\varepsilon_i(t_2)| = \sum_{i=1}^{K} |\varepsilon_{Pi}(t_1) + \Delta\varepsilon_{Pi}| + |\varepsilon_{N1}(t_1) - \varepsilon_{N1}(t_1)| + |\varepsilon_{N2}(t_1) - \varepsilon_{N2}(t_1)| + \cdots + |\varepsilon_{N\ell}(t_1) - \varepsilon_{N\ell}(t_1)| \tag{7.14}$$

For any area i with positive area component,

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_{Pi} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -\frac{B_s - B_{Pi}}{6} & \frac{B_{Pi}}{6} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon_{Pi} \\ \varepsilon_N(t_1) - \Delta\varepsilon_{Pi} - \varepsilon_N(t_1) \end{bmatrix} = \begin{bmatrix} 0 \\ (-\frac{B_s}{6}) \cdot (\Delta\varepsilon_{Pi}) \end{bmatrix} \tag{7.15}$$

For any area j with negative area component,

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_{Nj} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -\frac{B_s - B_{Nj}}{6} & \frac{B_{Nj}}{6} \end{bmatrix} \begin{bmatrix} -\varepsilon_{Nj}(t_1) \\ \varepsilon_N(t_1) - \varepsilon_N(t_1) + \varepsilon_{Nj}(t_1) \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ (-\frac{B_s}{6}) \ (-\varepsilon_{Nj}(t_1)) \end{bmatrix} \tag{7.16}$$

Once Eqs. 7.15 and 7.16 hold, the areas with negative area components of ε_j reduce their respective area component of ε_j to zero and, hence, become not responsible for creating accumulated regulating deficiencies. Areas with positive area components of ε_i also reduce their respective area component of ε_i and become less responsible for creating accumulated regulating deficiencies. From Eqs. 7.15 and 7.16, there is no change in the system time deviation, but only changes in inadvertent interchanges will occur.

B. Debit/Credit System

Considering the operation of all the interconnection, the total amount of regulation for the correction scheme discussed in Section A of this chapter is

$$\sum_{i=1}^{K} |\Delta\varepsilon_{Pi}| + \sum_{j=1}^{\ell} |\Delta\varepsilon_{Nj}| = 2 \cdot |\varepsilon_P(t_1)| \tag{7.17a}$$

when $\varepsilon(t_1) \leqq 0$.

$$\sum_{i=1}^{K} |\Delta\varepsilon_{Pi}| + \sum_{j=1}^{\ell} |\Delta\varepsilon_{Nj}| = 2 \cdot |\varepsilon_N(t_1)| \tag{7.17b}$$

when $\varepsilon(t_1) \geqq 0$.

If some areas do not want to take the corrective control actions because of increasing regulating costs and increasing disparity in incremental costs during the course of a day [4], a debit/credit system can be used to determine the associated regulation costs. The following situations are recognized.

a) When $\varepsilon(t_1) < 0$, let the basis energy cost be λ_L(\$/MWH). Areas with area components of system time deviation can sell their respective component $\varepsilon_{Pi}(t_1)$ to areas with negative area components of system time deviation at the rate of $(- \frac{B_s}{6}) \cdot \lambda_L$ (\$/sec). Instead of having debit or credit, Eqs. 7.9 or 7.10

can be used so that each area may adjust its inadvertent interchange.

b) When $\varepsilon(t_1) \geq 0$, the following is considered. Areas with negative components of system time deviation can sell their respective component $\varepsilon_{Nj}(t_1)$ to areas with positive area components at a rate of $(-\frac{B_s}{6}) \cdot \lambda_L$(\$/sec), where λ_L is the basis energy cost. Again, instead of having debit or credit, Eqs. 7.15 or 7.16 can be used so that each area may adjust its inadvertent interchange.

Three examples are given below for the Eastern System regulation survey. The computation of debit/credit of each area is based on Q area components of system time deviation (Table 4.2).

1. Example 1

Table 7.1 shows the initial system time deviation and inadvertent interchanges of the six regions in the interconnection. From these, the area time deviation components can be calculated. Their values are the same as the accumulated regulating deficiencies (MWH) divided by the common factor $(-\frac{B_s}{6})$.

A basis energy rate of λ_L = \$10/MWH will be used. The corresponding ε_i rate, determined by $[(-\frac{B_s}{6}) \cdot \lambda_L]$, is 8893.3 (\$/sec). Consider two areas with components of ε_i of opposite signs, e.g., areas 1 and 4. The two areas may elect to mutually settle their time error components. In this case, area 1 sells its time error component of .18861 (sec) to area 4, and area 1 receives \$1677.4 from area 4. They may also elect to adjust their ε_i components independently. In this case, the area component of area 1 is adjusted to zero and I_1 is adjusted to 476.26

Table 7.1. Debit/credit computations for example 1

Region	Initial Conditions				After Accounting	
	Inadvertent Energy I_i (MWH)	Time Error Component ε_i (sec)	Accumulated Regulating Deficiencies $(-B_s/6)\cdot\varepsilon_i$	$	Inadvertent Energy I_i (MWH)	Time Error Component ε_i (sec)
1	644	.18861	167.74	+1677.4	476.26	0
2	223	.01147	10.2	+ 102	212.80	0
3	- 179	- .82055	- 729.74	- 102	- 168.80	- .80908
4	-1205	-2.0215	-1797.79	-1677.4	-1037.26	-1.8329
5	141	- .20550	- 182.76	0	141	- .20550
6	376	- .19250	- 171.20	0	376	- .19250
Total	0	-3.040	-2703.55	0	0	-3.040

(MWH) from Eq. 7.9. For area 4, ε_4 is adjusted to -1.8329 (sec) and I_4 is adjusted to -1037.26 (MWH). These data are shown in Table 7.1.

Since areas 2 and 3 have components of ε_i of opposite signs, similar arrangements can be made between them. If area 2 sells its component of .01147 (sec) to area 3, area 2 receives \$102 from area 3. ε_2, I_2, ε_2, and I_3 are correspondingly adjusted.

After settling their accounts according to the above debit/credit computerations, areas 1 and 2 will no longer have accumulated regulating deficiencies and will have no further obligations to regulate. At the same time, the regulation obligation of areas 3 and 4 are reduced. Areas 5 and 6 are still responsible for their respective initial component of $\varepsilon_i(t_1)$; their regulation obligations are unchanged.

If areas 3, 4, 5, and 6 reduce their respective components of ε_i to zero by the correction control action, the sytem time deviation will return to zero. A total amount of system regulation of 2703.56 (MWH) will be required.

2. Example 2

Consider areas 3, 4, 5, and 6 with negative components of ε_i. These areas may decide to "settle" their accounts with areas 1 and 2, which have positive components of ε_i. If they want to purchase area components of ε_i from areas 1 and 2, there may be many types of arrangements between regions. In this example, it is assumed that areas 3, 4, 5, and 6 purchase area components of ε_i from areas 1 and 2 according to their bias ratios. Note that the sum of area components of ε_i of areas 1 and 2 is .2 (sec). The transactions for areas 3-6 are :

Area 3: purchases (1087/3876) x .2 = .05468 sec (pay \$486.27).

Area 4: purchases (1170/3976) x .2 = .05885 sec (pay \$523.40).

Area 5: purchases (639/3976) x .2 = .03214 sec (pay \$285.86).

Area 6: purchases (1080/3976) x .2 = .05433 sec (pay \$483.14).

Table 7.2 shows the accounting and the subsequent adjustments. The regulation obligations for areas 3, 4, 5, and 6 are reduced, while areas 1 and 2 will have no further regulation obligations. It is to be noted that inadvertent interchange energies of areas 5 and 6 (whose initial operating point is in the 2-B sector of (ε, I) plane) are increased.

If areas 3, 4, 5, and 6 reduce their respective components of ε_i to zero by the corrective control action, the system time deviation will return to zero. A total amount of system regulation of 2703.56 (MWH) will be required.

3. Example 3

If all the control areas agree to reduce their respective inadvertent interchange energy to zero, i.e., $I_i \to 0$ for $i=1,2,\cdots,Q$, without affecting the system time deviation, from Eq. 4.1:

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} 0 \\ -I_i(t_1) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \left(-\frac{B_s}{6}\Delta\varepsilon_{ic}\right) \qquad i=1,2,\cdots,Q \qquad (7.18)$$

Then, at $t=t_2$,

$$\begin{bmatrix} \varepsilon(t_2) \\ I_i(t_2) \end{bmatrix} = \begin{bmatrix} \varepsilon\ (t_1) \\ I_i(t_1) \end{bmatrix} + \begin{bmatrix} \Delta\varepsilon \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} \varepsilon(t_1) \\ 0 \end{bmatrix} \qquad i=1,2,\cdots,Q \qquad (7.19)$$

From Eqs. 3.7 and 7.19,

Table 7.2. Debit/credit computations for example 2

	Initial Condition			After Accounting	
Region	I_i (MWH)	ε_i (sec)	$\$_i$	I_i (MWH)	ε_i (sec)
1	644	.18861	+1677.4	476.26	0
2	223	.01147	+ 102	212.80	0
3	-179	- .82055	- 486.27	- 130.37	- .76587
4	-1205	-2.0215	- 523.40	-1152.66	-1.96265
5	141	- .2055	- 285.86	169.58	- .17336
6	376	- .1925	- 483.14	424.32	- .13817
Total	0	-3.04	≅0	0	-3.04

$$\begin{bmatrix} \varepsilon_i(t_2) \\ \varepsilon_r(t_2) \end{bmatrix} = \left(-\frac{6}{B_s}\right) \begin{bmatrix} -B_i/6 & 1 \\ -B_r/6 & -1 \end{bmatrix} \begin{bmatrix} \varepsilon(t_2) \\ I_i(t_2) \end{bmatrix} = \begin{bmatrix} y_i\varepsilon(t_1) \\ y_r\varepsilon(t_1) \end{bmatrix}$$

$$i=1,2,\cdots,Q \qquad (7.20)$$

where $y_i = B_i/B_s$.

Equation 7.20 shows that, to reduce its inadvertent energy to zero, an area i should adjust its own area component of system time deviation to $[y_i \cdot \varepsilon(t_1)]$. Table 7.3 shows the initial conditions and the desired conditions of areas.

Comparing the initial and desired values, we can make the following observations.

a) Initially, areas 1 and 2 (whose initial operating points are in the 2-A sector of their respective (ε, I) plane) are responsible for positive area components of system time deviation. It is desirable for these areas to reduce their respective area components of ε_i to zero. However, at the desired conditions, areas 1 and 2 become responsible for negative area components of system time deviation. In other words, more regulation is required to return these negative area components of system time deviation to zero.

b) Areas 3 and 4 (whose initial operating points are in the third quadrant of their respective (ε, I) plane) reduce their respective area components of system time deviation. Their area components of system time deviation are adjusted in the desired

Table 7.3. Debit/credit computations for example 3

	Initial Condition		Desired Condition		
Region	I_i (MWH)	ε_i (sec)	I_i (MWH)	ε_i (sec)	$\$_i$
1	644	.18861	0	- .53553	30253
2	223	.01147	0	- .23928	12870
3	- 179	- .82055	0	- .61928	- 6457
4	-1205	-2.0215	0	- .66657	-67689
5	141	- .2055	0	- .36405	8469
6	376	- .1925	0	- .61529	22560
Total	0	-3.04	0	-3.04	0

direction and less regulation is required to achieve the desired conditions.

c) Areas 5 and 6 (whose initial operating points are in the 2-B sector of their respective (ε, I) plane) become more responsible for their respective area components of system time deviation. Their area components of system time deviation are adjusted in the wrong direction and more regulation is required to return their area components of ε_i to zero.

We conclude, therefore, that it is desirable for an area to reduce its own area component (of ε_i) to zero because less regulation is required. It is not desirable for an area to make its own area component (of ε_i) change in the direction away from the origin because more regulation would be required in that case.

1. Suggested debit/credit scheme

A proper debit/credit system should encourage the desirable adjustments of area components of system time deviation towards their respective origins. It should also discourage the undesirable adjustments of area components of system time deviation, i.e., adjustments that make ε_i move away from their respective origins. This can be done by using two different basis energy costs, λ_L and λ_H (\$/MWH).

As shown in Nathan Cohn's example of two-tier penalty/reward technique, we will illustrate the point by using

λ_L = \$10/MWH

$\lambda_H = 6\lambda_L$ = \$60/MWH

The criteria of computing debit/credit of each area can be suggested as follows.

a) An area can sell (purchase) a certain amount of area component of system time deviation at a lower rate λ_L (\$/MWH) to (from) the rest of the interconnection if area component (of system time deviation) of this area is adjusted in the direction toward the origin.

b) An area can sell (purchase) a certain amount of area component of system time deviation at a higher rate λ_H (\$/MWH) to (from) the rest of interconnection if area component (of system time deviation) of this area is adjusted in the direction away from the origin.

c) Only areas whose initial operating points are in the third (or first) quadrant can purchase (or sell) a certain amount of area component of system time deviation at a lower rate λ_L (\$/MWH) from (to) the rest of the interconnection.

Thus, areas 1 and 2 in example 3 can sell their respective initial area components, .18861 (sec) and .01147 (sec), at a lower ε_i rate, because these areas can make their respective regulation obligation to zero. However, areas 1 and 2 should sell their respective amount of area components, .53553 (sec) and .23928 (sec), at a higher ε_i rate, because these areas become responsible for negative area components of ε_i.

The basis energy rate λ_H = \$60/MWH will be used. The corresponding ε_i rate, determined by $[(-B_s/6)\cdot\lambda_H]$, is 53360 (\$/sec).

Area 1: .18861 x 8893.3 + .53553 x 53360 = \$30,253

Area 2: .01147 x 8893.3 + .23928 x 53360 = \$12,870

Areas 5 and 6 should sell their respective amount of area components at a higher rate because these areas become more responsible for regulation obligation.

Area 5: (-.2055 + .36405) x 53360 = \$8,460

Area 6: (-.1925 + .61529) x 53360 = \$22,560

Areas 3 and 4 can purchase energy from areas 1, 2, 5 and 6 at two different rates. It is assumed that areas 3 and 4 purchase energy at a lower rate from areas 1 and 2 by their bias ratio.

Area 3: Purchase $\left(\frac{B_3}{B_3+B_4}\right) \times .2 = .09632$ sec at a lower rate

Area 4: Purchase $\left(\frac{B_4}{B_3+B_4}\right) \times .2 = .10368$ sec at a lower rate

Then, computations of debit/credit of areas 3 and 4 become as

Area 3: -.09632 x 8893.3 + (-.82055 + .61928 + .09632) x 53360

= -\$6457

Area 4: -.10368 x 8893.3 + (-2.0215 + .10368 + .66657) x 53360

= -\$67689

These data are shown in Table 7.3. The sum of debit/credit of all the areas is zero. If all the areas reduce their respective adjusted area components of ε_i, the system time deviation will return to zero. A total amount of system regulation of 2703.56 (MWH) will be required.

VIII. DISCUSSIONS AND CONCLUSIONS

The results of this dissertation can be summarized as follows.

First, a control area can consider the system time deviation and its own inadvertent interchange as a vector with two coordinates. This vector can be decomposed into two vector components: a component caused by the area itself, and a component caused by the rest of the interconnection.

Because the vector is two-dimensional, this concept of the vector decomposition can be illustrated on two-dimensional Cartesian plane. This plane is called the (ε, I_i) plane. The vector components have the following properties on the (ε, I_i) plane.

1. A vector component caused by area i is on the line $I_i = \frac{-B_r}{6}\varepsilon$.
2. A vector component caused by area r is on the line $I_i = \frac{B_i}{6}\varepsilon$.
3. These two vector components are independent of each other.

Second, the effect of the AGC control actions in or outside area i is investigated on the (ε, I_i) plane. The effect of the corrective control actions in or outside area i is also investigated on the (ε, I_i) plane. These effects are illustrated in Figs. 3.3 and 3.4 and are summarized in Table 3.2.

The effect of some corrective control schemes are reviewed when there is a specific relationship between the corrective control actions among control areas. The present NERC-OC two-step corrective control scheme and the synchronized coordinated corrective control scheme proposed by Cohn are investigated.

Third, these corrective control schemes are compared in terms of energy required for the corrective control action. It is assumed that all areas return their respective operating point to the origin, i.e., zero time error and inadvertent interchange, after the corrective control action is completed. It is shown that the present two-step corrective control scheme involves unnecessary regulation (Table 4.3). If this scheme is modified, all areas can return their respective operating point to the origin with the same amount of regulation energy as that required for the synchronized coordinated correction.

Fourth, the causes of excessive accumulation of inadvertent interchanges in the WSCC system are investigated with the aid of the concept of vector decomposition. Six cases that can lead to excessive accumulation of inadvertent interchange of the area of interest are investigated using AGC simulation program. The results are compared to those when the area does not participate in the continuous automatic time deviation correction scheme. The causes of accumulation of inadvertent interchange that have been investigated are:

1. When some of the control areas do not participate in the system time deviation correction.
2. When the AGC control actions are superimposed upon the corrective control actions in and outside area i, the inadvertent interchange energy can be increased depending upon the sign and magnitude of the AGC control actions, $\Delta\varepsilon_{ig}$ and $\Delta\varepsilon_{rg}$.

Fifth, the validity of the decomposed vector components of the system time deviation and inadvertent interchange energy is checked using the AGC simulation program. The computer results show that:

1. A vector component caused by area i (either $\Delta\varepsilon_{ig}$ or $\Delta\varepsilon_{ic}$) is on the line parallel to the line $I_i = -\frac{B_r}{6}\varepsilon$.
2. A vector component caused by area r (either $\Delta\varepsilon_{rg}$ or $\Delta\varepsilon_{rc}$) is on the line parallel to the line $I_i = \frac{B_i}{6}\varepsilon$.
3. The operating point (ε, I_i) is the vector sum of these two components.

Sixth, considering the operation of the whole interconnection, the minimum regulation energy required to return the initial system error $\varepsilon(t_1)$ to zero is $(-\frac{B_s}{6})\cdot\varepsilon(t_1)$ (MWH). If all areas whose initial operating points are in certain sectors (2-A or 4-A) of the (ε, I) plane agree to sell their respective area component of ε_i to areas whose initial operating points are in certain sectors (the third or first quadrant) such that their ε_i components are of opposite sign, the system time deviation can be returned to zero with a minimum amount of energy for the corrective control action. This minimum regulation energy is equal to $(-\frac{B_s}{6})\cdot\varepsilon(t_1)$.

There are many ways to define debit/credit system. Three examples are presented. The debit/credit computations presented in this dissertation are based on Q area components of system time deviation. The debit/credit computations suggested by Cohn are based on Q primary components and Q(Q-1) secondary components of inadvertent interchange accumulations.

The computation of the debit/credit of control areas becomes quite simple.

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X. ACKNOWLEDGEMENTS

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XI. APPENDIX: THE AGC SIMULATION PROGRAM

A. Input Data and Formats

Card No.	Data	Dimension	Format
1	Number of areas (n)	-	I4
2	Scheduled frequency	Hz	F6.2
3,4,•••,n+2	No. of individual area	-	I4
	Governing bias	MW/.1Hz	F8.1
	Regulator bias	MW/.1Hz	F8.1
	Governing delay time	second	I4
	Governing action time	second	I4
	Regulator delay time	second	I4
	Regulator action time	second	I4
	Area generation capability	Mw	F8.1
	Scheduled generation	MW	F8.1
	Scheduled net interchange	MW	F8.1
	Area load	MW	F8.1
n+3	Event (GEN or LOAD)[1]	-	2A4
	Disturbance area	-	I4
	New value of generation or load	MW	F8.1

[1]Event control cards: LOAD causes a step change in load to occur in the disturbance area. New load should be specified. GEN causes a step change in generation to occur in the disturbance area. New generation should be specified. If there is no loss of generating unit, new value of system capacity should be blank. If there is loss of generating unit, new generation capacity must be specified.

Card No.	Data	Dimension	Format
	New value of system capacity	MW	F8.1
	Correction time H	hours	F8.3
n+4	Area tie-line measurement and schedule setting errors	MW	6F5.2
	Area frequency measurement and schedule setting errors	MW	6F5.2
n+5	Initial inadvertent interchange accumulation $I_i(0)$	MW	6F8.4
n+6	Correction type of each area		6I5
	0: No correction		
	1: Continuous, automatic I_i correction		
	2: Continuous, automatic ε correction		
	3: Continuous, automatic ε_i correction		
	4: Constant I_i correction		
	5: Constant ε correction		
	6: Constant ε_i correction		
n+7	Initial system time error $\varepsilon(0)$		F12.4
Other control cards[2]			

[2]Other control cards: TABLES (Format 2A4) causes a complete set of tables to be printed. RERUN (Format 2A4) causes all quantities to be reset to their initial values for preparation for additional event simulations for the same system. The program reruns another event case. RESTART (Format 2A4) returns to the top of the program to obtain new system for simulation. STOP (Format 2A4) indicates that all simulations have been completed and terminates the program.

B. Flow Chart of the AGC Program (ACNTRLP)

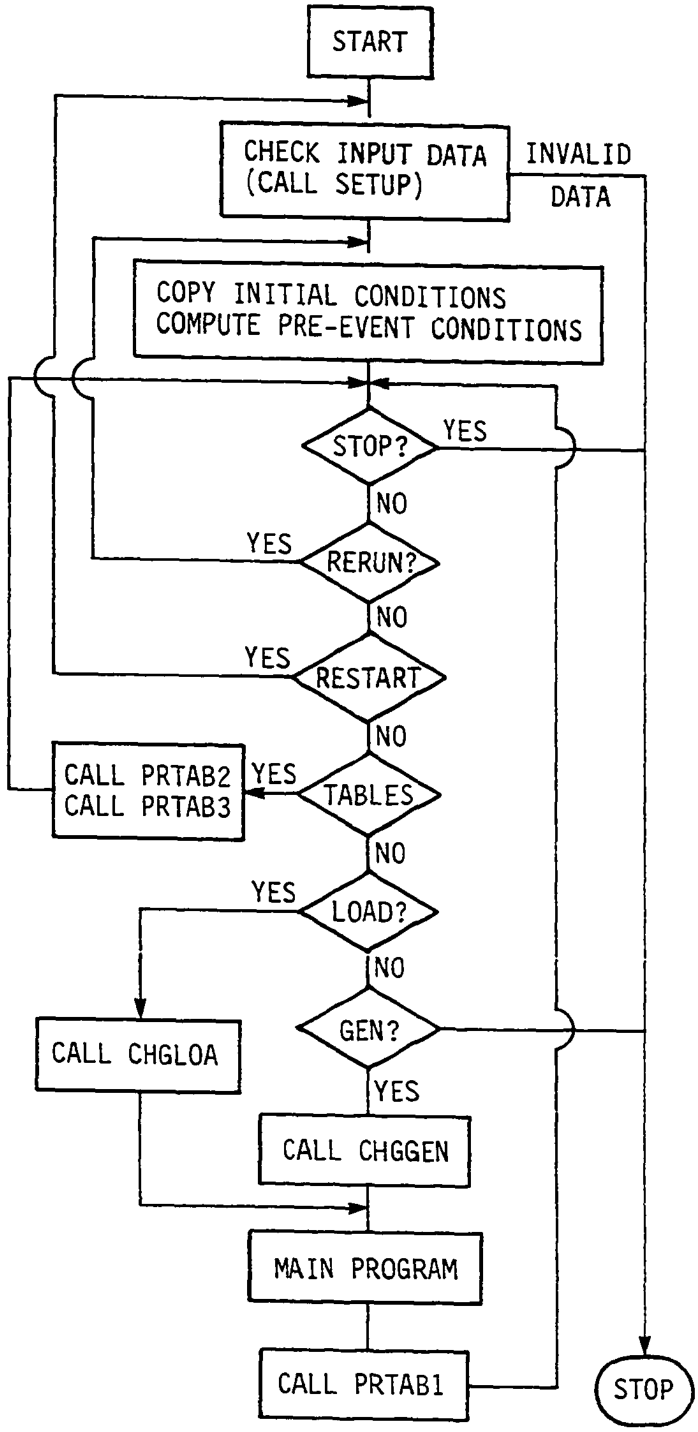

Figure 11.1. Flow chart of the AGC program (ACNTRLP)

C. System Representation

The natural frequency-power response of each area is represented by three straight lines, GG, LL, and CC, which represent the natural generation, load, and combined governing characteristic shown in Fig. 11.2. The governing bias β_i for area i and the system governing bias β_s are given as data as shown in Table 11.1. The governing bias of an area is defined as "the reciprocal of the slope of the area combined governing characteristic." The slope of the line CC of area i can be calculated from

$$MC_i = (.1)/\beta_i \quad \text{Hz/MW, } i=1,2,\cdots,n,n+1 \tag{11.1}$$

where n is the number of areas and (n+1) denotes the total system. The slopes of the lines GG and LL, MG_i and ML_i, are calculated from

$$MG_i = (4/3)\cdot MC_i,\ i=1,2,\cdots,n,n+1 \tag{11.2a}$$

$$ML_i = (-4)\cdot MC_i,\ i=1,2,\cdots,n,n+1 \tag{11.2b}$$

The constants in Eq. 11.2 are fixed in the program. IG_i and IL_i are frequencies at the intersections of the lines GG and CC with the frequency axis. Initial operating conditions of areas before the occurrence of a disturbance are given as data as shown in Table 11.2. IG_i and IL_i are given by

$$IG_i = f_s - MG_i\cdot G_{si},\ i=1,2,\cdots,n,n+1 \tag{11.3a}$$

$$IL_i = f_s - ML_i\cdot L_{si},\ i=1,2,\cdots,n,n+1 \tag{11.3b}$$

The subroutine SETUP checks data and prepares the values for the next step.

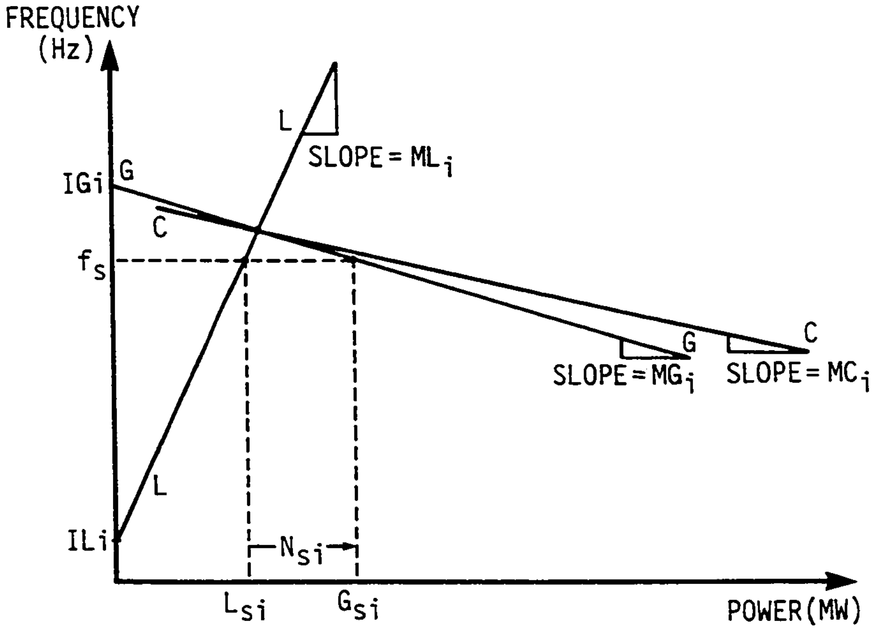

Figure 11.2. The generation and load governing characteristic

AREA	GOVERNING BIAS B_i (MW/·1Hz)	REGULATOR BIAS B_i (MW/·1Hz)
1	-4	-4
2	-8	-8
3	-5	-5
SYSTEM	-17	-17

Table 11.1. Example of bias characteristics

Table 11.2. Example of initial operating condition[a]

Area	Area Capability (MW)	Scheduled Generation (MW)	Net Interchange (MW)	Area Load (MW)
1	1,000	600	150	450
2	1,000	500	- 50	550
3	1,000	400	-100	500
System	3,000	1,500	0	1,500

[a]Initial frequency $f = f_s = 60$ Hz.

D. Sequence of Events

The sequence of events corresponding to each of three types of disturbances is shown in Figs. 11.3-11.5. Initially, the system is in a steady-state condition indicated by point 0. At $t=t_o$, an event causing an unbalance between generation and load occurs. The governors do not receive a signal to adjust the generation until some time later (in the order of a few seconds). Consequently, the energy required to balance the system generation and load comes from the stored kinetic energy in the system, causing the frequency to change. For example, for a sudden increase in load, the frequency drops to a value f_1 at $t=t_1$. In actual power system operation, f_1 is dependent upon several factors including the time required for the governors to receive a signal as well as the frequency-power relationships of the system gneration and load. The governors start to respond at $t=t_1$. At time $t=t_2$, which corresponds to point 2, they complete their initial response. Up until this time, the supplementary regulation has been prohibited from operating. Supplementary action produces a new steady-state operating point 3 at the scheduled frequency f_s.

1. Step change in load

Assume the step change of load ΔL_K in area K, then the new load L'_K and the new system load L'_{n+1} are

$$L'_K = L_K + \Delta L_K \tag{11.4a}$$

$$L'_{n+1} = L'_K + \sum_{\substack{i=1 \\ i\neq k}}^{n} (L_i) \tag{11.4b}$$

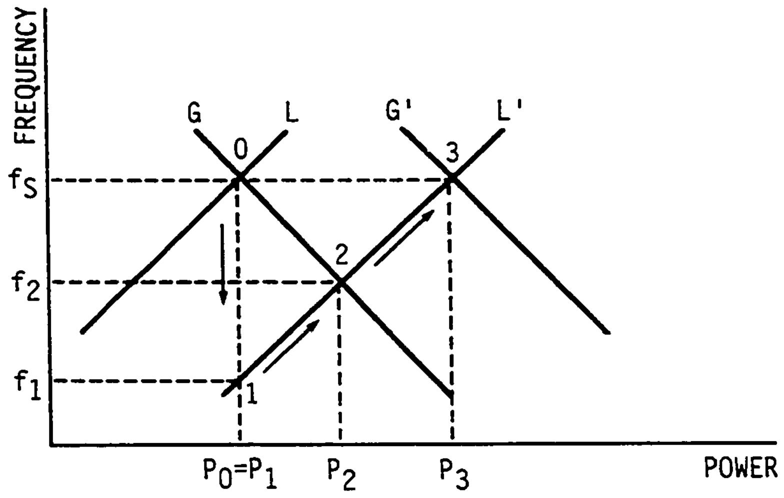

Figure 11.3. Sequence of events for a step change in load

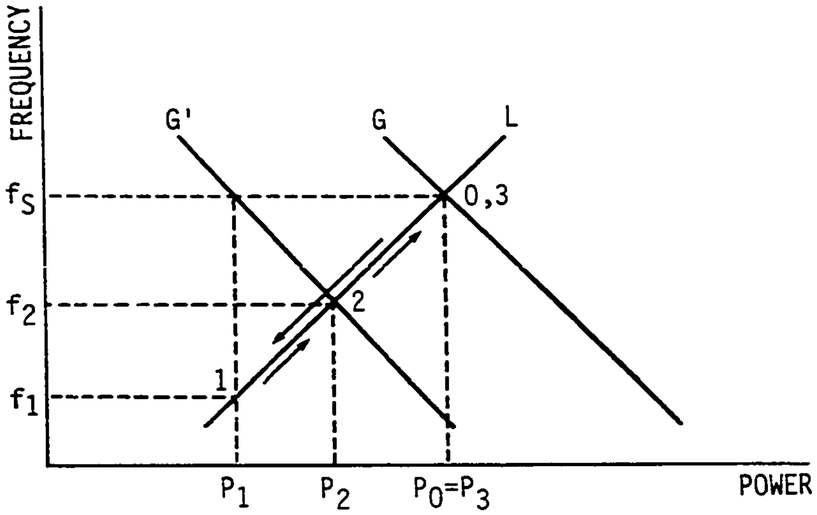

Figure 11.4. Sequence of events for a step change in generation

These changes in load alter the load intercepts of area K and the system to new values, IL'_K and IL'_{n+1}.

$$IL'_K = f_s - (ML_K)(L'_K) \tag{11.5a}$$

$$IL'_{n+1} = f_s - (ML_{n+1})(L'_{n+1}) \tag{11.5b}$$

The frequency f_1 is calculated from

$$f_1 = IL'_s + (ML_{n+1})(L_{n+1}) \tag{11.6}$$

Point 2 is the intersection of the lines G and L', as shown in Fig. 11.3. The generation $G_{n+1}(t_2)$ can be determined from

$$G_{n+1}(t_2) = (IG_{n+1} - IL'_{n+1})/(ML_{n+1} - MG_{n+1}) \tag{11.7}$$

The frequency f_2 is

$$f_2 = IL'_{n+1} + (ML_{n+1}) \cdot G_{n+1}(t_2) \tag{11.8}$$

2. Step change in generation

Assume a step change in generation ΔG_K (negative) in area K. Then, the new generation G'_K and the new system generation G'_{n+1} are

$$G'_K = G_K + G_K \tag{11.9a}$$

$$G'_{n+1} = G'_K + \sum_{\substack{i=1 \\ i \neq K}}^{n} (G_i) \tag{11.9b}$$

These changes in generation alter the generation intercepts of area K and the system to new values, IG'_K and IG'_{n+1}.

$$IG'_K = f_s - (MG_K)(G'_K) \tag{11.10a}$$

$$IG'_{n+1} = f_s - (MG_{n+1})(G'_{n+1}) \tag{11.10b}$$

Point 2 is the intersection of the lines G' and L, as shown in Fig. 11.4. The generation $G_{n+1}(t_2)$ is given by

$$G_{n+1}(t_2) = (IL_{n+1}-IG'_{n+1})/(MG_{n+1}-ML_{n+1}) \quad (11.11)$$

The frequency f_2 is

$$f_2 = IG'_{n+1} + (MG_{n+1})\cdot G_{n+1}(t_2) \quad (11.12)$$

3. Step change in generation with a loss of generating unit

Since this change in generation occurs as the direct result of a loss of generating unit, the generating capability of area K also changes from C_K to C'_K. These changes alter both the generation slope and the generation intercept of area K as well as that of the system. The governing bias is assumed to be proportional to the available capability in each area (Fig. 11.5).

Assume that the step change in generation ΔG_K occurs in area K. Then,

$$G'_K = G_K + \Delta G_K$$

where ΔG_K is negative (11.13)

$$MG'_K = C_K \cdot MG_K/C'_K \quad (11.14)$$

The new system generation G'_{n+1} is

$$G'_{n+1} = G'_K + \sum_{\substack{i=1 \\ i\neq K}}^{n} (G_i) \quad (11.15)$$

The new value of the system generation slope then can be determined from

$$MG'_{n+1} = (4/3)(.1)/[\sum_{\substack{i=1 \\ i\neq K}}^{n} (\beta_i) + \beta_K C'_K/C_K] \quad (11.16)$$

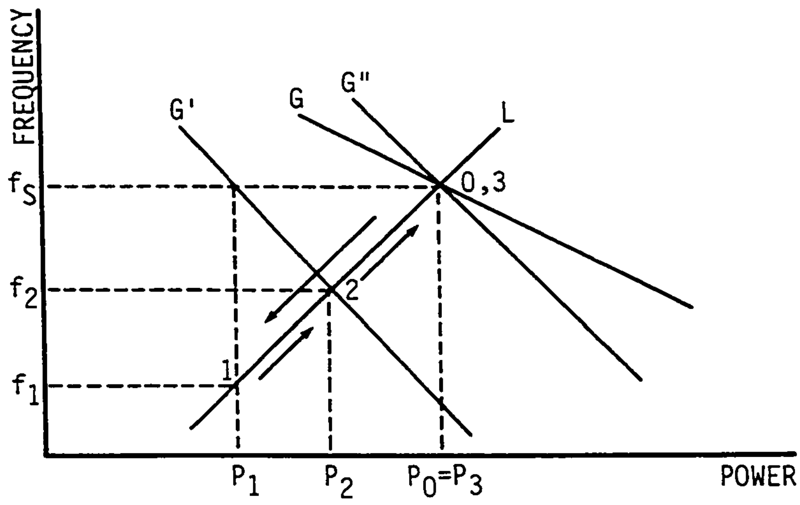

Figure 11.5. Sequence of events for a step change in generation involving a loss of a generating unit

The new generation intercepts IG'_K and IG'_{n+1} can be determined from

$$IG'_K = f_s - (MG'_K)(G'_K) \quad (11.17)$$

$$IG'_{n+1} = f_s - (MG'_{n+1})(G'_{n+1}) \quad (11.18)$$

The value of the frequency f_1 can now be computed from

$$f_1 = IL_{n+1} + (ML_s)(G'_s) \quad (11.19)$$

The generation $G_{n+1}(t_2)$ is given by

$$G_{n+1}(t_2) = (IL_{n+1} - IG'_{n+1})/(MG'_{n+1} - ML_{n+1}) \quad (11.20)$$

The frequency f_2 is equal to

$$f_2 = IG'_s + (MG_s)\cdot G_{n+1}(t_2) \quad (11.21)$$

The calculations shown here are done by the subroutines CHGLOA and CHGGEN. The subroutine CHGLOA is used for a step change in load and the subroutine CHGGEN is used for a step change in generation with and without a loss of generating unit.

E. Governor Response

Since the frequencies f_1, f_2 and the system generation $G_{n+1}(t_1)$ and $G_{n+1}(t_2)$ were determined for any kind of disturbance, the intermediate values of variables can be determined. An exponential response rate is selected in preference to a linear or other response rate. Each time increment is current set to four seconds.

At the current time t, a response factor $FACT_i$ of area i is computed by

$$FACT_i = 1 - EXP\ [-5(t-t_1)/(t_2-t_1)] \quad (11.22)$$

where

t_1 is the initial time for governing action

t_2 is the final time for governing action

If $FACT_i$ is greater than .993, then it is assumed to be equal to 1.000.

The current generation $G_i(t)$ of area i can be calculated by

$$G_i(t) = G_i(t_1) + (FACT_i)\cdot(G_i(t_2)-G_i(t_1)) \qquad (11.23)$$

After the above calculations are finished for all the areas, the current system generation $G_{n+1}(t)$ is

$$G_{n+1}(t) = \sum_{i=1}^{n} G_i(t) \qquad (11.24)$$

The current frequency f(t) is computed by

$$f(t) = IL_s(t_1) + (ML_i)\cdot G_{n+1}(t) \qquad (11.25)$$

The current load and net interchange can be computed from

$$L_i(t) = (f(t)-IL_i(t_1))/ML_i, \quad i=1,2,\cdots,n,n+1 \qquad (11.26)$$

$$N_i(t) = G_i(t) - L_i(t), \quad i=i,2,\cdots,n,n+1 \qquad (11.27)$$

The initial time t_1 and final time t_2 are read from data, as shown in Table 11.3.

F. Supplementary Regulation Response

From Table 11.3, regulator delay times should be greater than the sum of the governing delay and action times for each area. Let t_2' be the initial time of regulating action for area i. When area control error

Table 11.3. Example of area delay and action times

	Governing[a]		Regulator[a]	
Area	Delay (sec)[b]	Action (sec)[c]	Delay (sec)[b]	Action (sec)[c]
1	4	16	28	52
2	4	12	24	52
3	4	16	28	52
System	4	16	24	52

[a]The time delays of the regulators must be greater than the sum of the governing delay and action times for each area.

[b]Relay times are measured from the occurrence of the disturbance until responses occur.

[c]Actual response times after appropriate time delays.

ACE_i is not zero at $t=t_2'$, the regulator shifts the generation characteristic of that area. The regulator action times in Table 11.3 are considered as five times the regulator time constant so as to include the continuous automatic correction schemes and the error terms (VERSION B). This is the main difference between VERSION A and VERSION B.

For the current time $t \geq t_2'$, $ACE_i(t)$ is calculated from

$$ACE_i(t) = (N_i(t)-N_{si}(t)) - 10\ B_i \cdot (f(t)-f_s) - \tau_i(t) + 10\ B_i\phi_i(t) - CORR_i(t) \quad (11.28)$$

Tie-line power measurement or scheduling error $\tau_i(t)$ and frequency measurement or scheduling error $\phi_i(t)$ are read as data and they should be constant. Each correction term $CORR_i(t)$ can be any of the following for $t \geq t_2'$.

i) $CORR_i(t) = 0$ when an area does not particpate any correction at all.

ii) $CORR_i(t) = -\frac{1}{H} I_i(t)$ when an area wants to correct its current inadvertent accumulation $I_i(t)$ continuously.

iii) $CORR_i(t) = \frac{B_i}{6H} \varepsilon(t)$ when an area wants to correct the current time error $\varepsilon(t)$ continuously.

iv) $CORR_i(t) = -\frac{1}{H} (I_i - \frac{B_i}{6} \varepsilon)$ when an area wants to correct the current area time error component $\varepsilon_i(t)$ continuously.

v) $CORR_i(t) = -\frac{1}{H} I_i(t_o)$ when an area wants to correct the initial inadvertent accumulation $I_i(t_o)$.

vi) $CORR_i(t) = \frac{B_i}{6H} \varepsilon(t_o)$ when an area wants to correct the initial time error $\varepsilon(t_o)$.

vii) $CORR_i(t) = -\frac{1}{H}\,(I_i(t_o) - \frac{B_i}{6}\,\varepsilon(t_o))$ when an area wants to correct the initial time error component $\varepsilon_i(t_o)$.

The correction time H, the initial values of time error and inadvertent accumulation of areas, and the type of correction scheme are read as data.

If the area control error (as shown in Eq. 11.28) is not zero, the regulator shifts the generation characteristic of the area. Consequently, the generation intercept of the area will be shifted. However, the load intercept will remain the same. The generation intercept at the next time step $(t+\Delta T)$ can be calculated from

$$IG_i(t+\Delta T) = f_s - (MG_i)\ [(f_s - IG_i(t))/MG_i - (FACT_i)\cdot ACE_i(t)] \qquad (11.29)$$

where

$$FACT_i = 1 - EXP\ [(-5)(\Delta T)/(t_3 - t_2')] \qquad (11.30)$$

when t_2' is not given as a multiple of four seconds, and let $m\Delta T < t_2' < (m+1)\Delta T$. $IG_i((m+1)\Delta T)$ can be calculated from

$$IG_i((m+1)\Delta T) = f_s - (MG_i)\ [(f_s - IG_i(m\Delta T))/MG_i - (FACT_i)\cdot ACE_i(m\Delta T)] \qquad (11.31)$$

where

$$FACT_i = 1 - EXP\ [(-5)((m+1)\Delta T - t_2')/(t_3 - t_2)] \qquad (11.32)$$

Once the new governing intercept $IG_i(t+\Delta T)$ is found for each area, the frequency $f(t+\Delta T)$ can be found. At the time $t+\Delta T$,

$$f = IG_i + MG_i \cdot G_i \qquad (11.33a)$$

$$f = IL_i + ML_i \cdot L_i \qquad (11.33b)$$

The total generation is equal to the total load, i.e.,

$$\sum_{i=1}^{n} (G_i) = \sum_{i=1}^{n} (L_i) \tag{11.34}$$

From Eqs. 11.33a and b and 11.34,

$$f = \frac{\sum_{i=1}^{n} (IG_i/MG_i) - \sum_{i=1}^{n} (IL_i/ML_i)}{\sum_{i=1}^{n} (1/MG_i) - \sum_{i=1}^{n} (1/ML_i)} \tag{11.35}$$

Once the current frequency $f(t+\Delta T)$ is known, the generation and load of each area at $(t+\Delta T)$ can be found from Eqs. 11.33a and b. The net interchange is computed from

$$N_i(t+\Delta T) = G_i(t+\Delta T) - L_i(t+\Delta T), \; i=1,2,\cdots,n,n+1 \tag{11.36}$$

$ACE_i(t+\Delta T)$ is then calculated from Eq. 11.28. If the absolute value of ACE_i is larger than .01, then the computations in Eqs. 11.28-11.36 are repeated, and ACE_i at the next time increment is calculated.

The correction terms are set very small in actual power system operation. In other words, the correction time H is set very large. In order to obtain rapid convergence of area control errors, H is set much smaller than actually used in practice.