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# Control Strategy for Load Frequency Control to Manage TRANSCO Reserve in Restructured Power System

**Lekshmi R. R., S. Balamurugan**

***Abstract*: Load frequency control existing in restructured power system retains frequency change and transmission line power variations within limits. Tie line bias control strategy adopted for load frequency control allows only contracted power to flow through transmission line. Thus, during violation, this strategy does not allow transmission companies to utilize its available reserve beyond the contract. Concurrently, only same area generation units are rescheduled to satisfy violations. This paper proposes a new control strategy for load frequency control in a competitive environment considering transmission line reserve. The strategy allows the use of more economic generating units located in neighbouring areas, thereby making use of transmission company's reserve up to the maximum limit during violation. The proposed strategy is tested for its effective and efficient performance under bilateral and poolco model with various contract violations. The strategy proves for the effective utilization of neighbouring generating units that offers lowest prices thereby making the system efficient.***

***Keywords*: Congestion management, Deregulated power system, Load frequency control.***

## I. INTRODUCTION

Introduction of competitive market in power sector unbundles vertically integrated industry into individual entities called GENerating COmpanies (GENCOs), TRANSmission COmpanies (TRANSCOs), DIStribution COmpanies (DISCOs) and Independent System Operator (ISO) [1]. The restructured system maintains vertical system structure, but differs in operation [2-3]. ISO supervises the operation based on competition and contract [4-6]. The new paradigm introduces power trading under different market, namely single-buyer, bilateral and poolco. The market power under different models is based on either auction procurement or negotiations.

ISO provides many ancillary services in order to maintain system stability and reliability [7]. One such service is Load Frequency Control (LFC) [8]. The main goal of LFC in vertical power system is to maintain frequency at nominal value by matching generation with demand besides minimizing tie line power deviations.

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LFC performance is improved through different secondary controllers under tie line bias strategy [9-13].

In restructured system, LFC aims to ensure contract based GENCOs and TRANSCO power [14-17]. Handling violations within system capability and capacity is a big challenge faced by ISO. All LFC researches [14-23] under deregulated environment adopt tie line bias control. During violation, tie line bias control maintains TRANSCO power at scheduled value by permitting same area GENCOs to compensate for violated demand. However, there can be GENCOs in neighbouring area that compensate more economically than same area GENCOs. The existing strategy does not make use of these economical GENCOs. Meanwhile, maintaining TRANSCO power at scheduled value, this strategy does not make use of its reserve even if available. Hence it is necessary to reconfigure existing tie line bias control so as to make it suitable for utilizing TRANSCO reserve [24].

In this paper, a new strategy is proposed which decides secondary controller input of LFC based on economic factor and available TRANSCO reserve. During violation, the economic participation of GENCOs from other area makes TRANSCO power to vary from scheduled value. However, if the violation results in TRANSCO line congestion, this strategy adapts itself and reschedules generation such that TRANSCO power is maintained at limit, compromising economics. The developed strategy is verified in two area power system under bilateral and poolco model for various violations. The new strategy works effectively by allowing willing neighbouring area GENCOs with less offer price, to participate in compensating the violated demand.

The restructured power system chosen for the study is presented in Section 2. Section 3 presents operation of LFC in restructured environment. The new strategy to ensure maximum usage of TRANSCO reserve is given in Section 4. Section 5 reports testing of proposed strategy in bilateral and poolco model for different violations. The developed mathematical models are considered under contract and violation. Each model is subjected to two different violations which results in TRANSCO power below and above limit. The performance comparison of proposed with existing tie line bias control are done for these violations. Conclusions are derived in Section 6.

## II. RESTRUCTURED POWER SYSTEM

Power trading [25] in restructured power system is carried out in a competitive manner.

Market takes either single-buyer, bilateral or poolco model. In single-buyer model [26] ISO sketches supply curve in increasing order of offer price against vertical line that corresponds to predicted demand for respective time slot. The market is cleared at the intersection between supply and demand curves. The point is extrapolated to x and y axis to get market power and market clearing price. The players to the left of intersection point in demand curve are announced as winners. These GENCOs are allowed to trade based on allotted power. Bilateral model [27] allows any GENCOs and DISCOs to enter into negotiations and make final settlements for any amount of power at a contracted price during any time period. In poolco model [28], ISO plots supply and demand curves in ascending and descending order of offer and bid price respectively for a time slot. It then announces all players to left of intersection point of two curves as winning players. Power trading is performed between these GENCOs and DISCOs. This paper considers two area deregulated system with two winning GENCOs and DISCOs in each area under bilateral and poolco model. Each GENCO generates scheduled power to meet demand of each area/DISCO. This is performed with the help of LFC. To analyse LFC performance, it is necessary to develop mathematical model of system.

## III. OPERATION OF LFC IN RESTRUCTRED POWER SYSTEM

Mathematical model of two area deregulated system is developed and furnished in Fig. 1. To illustrate the performance of proposed strategy, present study considers two area power system operating under bilateral and poolco model. The two area deregulated system, operating under bilateral model, allows GENCOs to meet contracted power of DISCO. The participation of GENCO (*pf* given in Fig. 1) to meet scheduled demand of a GENCO is given by contract participation factor (*cpf*). *cpf* makes DISCO Participation Matrix (*DPM*) as per equation (1).

$$DPM = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \quad (1)$$

The rows and columns of *DPM* represent GENCOs and DISCOs respectively. Sum of any column elements is unity. Using *cpf*, GENCOs contracted power is calculated using equation (2).

$$P_{Gk} = \sum_{j=1}^{4} cpf_{kj} \times P_{Lj};\ k=1 \text{ to } 4 \quad (2)$$

Where, $P_{Lj}$ represents scheduled demand of $j^{th}$ DISCO.

The power export ($P_{exp-1}$) and import ($P_{imp-1}$) from and to area-1 is given in equation (3) and (4).

$$P_{exp-1} = \sum_{j=3}^{4}\sum_{k=1}^{2} cpf_{kj} \times P_{Lj} \quad (3)$$

$$P_{imp-1} = \sum_{i=1}^{2}\sum_{l=3}^{4} cpf_{li} \times P_{Li} \quad (4)$$

Where,

$P_{Li}$ represents demand of $i^{th}$ DISCO in area-1

$P_{Lj}$ represents demand of $j^{th}$ DISCO in area-2

When the system operates under poolco model, GENCO meets its contracted area demand. The participation of GENCO (*pf* given in Fig. 1) to meet scheduled area demand is given by area participation factor (*apf*). *apf* forms Area Participation Matrix (*APM*). *APM* for GENCOs in area-1 and area-2 are shown in equations (5) and (6).

$$APM_1 = \begin{bmatrix} apf_{11} & apf_{12} \\ apf_{21} & apf_{22} \end{bmatrix} \quad (5)$$

$$APM_2 = \begin{bmatrix} apf_{31} & apf_{32} \\ apf_{41} & apf_{42} \end{bmatrix} \quad (6)$$

$apf_{12}$ in equation (5) corresponds to participation of GENCO1 to meet demand in area-2.

The power output of $k^{th}$ GENCO to meet demand of $j^{th}$ area is calculated as per equation (7).

$$P_{Gk} = \sum_{j=1}^{2} apf_{kj} \times P_{Lj};\ k=1 \text{ to } 4 \quad (7)$$

Where,

$P_{Lj}$ represents scheduled demand in $j^{th}$ area

The power export ($P_{exp-1}$) and import ($P_{imp-1}$) from and to area-1 is given in equation (8) and (9).

$$P_{exp-1} = \sum_{k=1}^{2} apf_{k2} \times P_{L2} \quad (8)$$

$$P_{imp-1} = \sum_{l=3}^{4} apf_{l1} \times P_{L1} \quad (9)$$

Where,

$P_{L1}$ represents area-1 demand

$P_{L2}$ represents area-2 demand

For the mathematical model of system given in Fig. 1, net power exchange through TRANSCO is obtained by considering demand of area-2 met by area-1 GENCOs ($P_{exp-1}$) and demand of area-1 met by area-2 GENCOs ($P_{imp-1}$) and is as per equation (10).

$$\Delta P_{tie12scheduled} = P_{exp-1} - P_{imp-1} \quad (10)$$

The difference between actual and scheduled TRANSCO power gives error as in equation (11).

$$\Delta P_{tie12\ error} = \Delta P_{tie12actual} - \Delta P_{tie12scheduled} \quad (11)$$

During violation, GENCO compensates for unscheduled demand of an area based on economic participation factor (*epf*). epf is decided based on the offer price of each GENCO willing to participate in LFC during contract violation. This is given in equation (12).

$$epf_i = \frac{(1/Price_i)}{\sum_{j=1}^{Nwg}(1/Price_j)} \quad (12)$$

Equation (12) sets the *epf* value such that the value is higher for the GENCO offering lowest price. The sum of all *epf* values is equal to unity. The power of $k^{th}$ GENCO to meet unscheduled demand of $j^{th}$ area or DISCO is calculated using equation (13).

$$P_{Gk\_new} = P_{Gk} + epf_k \times P_{Dj};\ k=1 \text{ to } 4 \quad (13)$$

Where,

$P_{Gk}$ represents contract power of $k^{th}$ GENCO

$epf_k$ is the *epf* of $k^{th}$ GENCO

$P_{Dj}$ is unscheduled demand in $j^{th}$ area/DISCO

The cost incurred in meeting the unscheduled power by all willing GENCOs is given in equation (14).

$$cost = \sum_{k=1}^{N} epf_k \times \Delta P_{Dj} \times price_{off-unk} \quad (14)$$

Where,

$epf_k$ is the *epf* of $k^{th}$ GENCO

$P_{Dj}$ is unscheduled demand in $j^{th}$ area/DISCO

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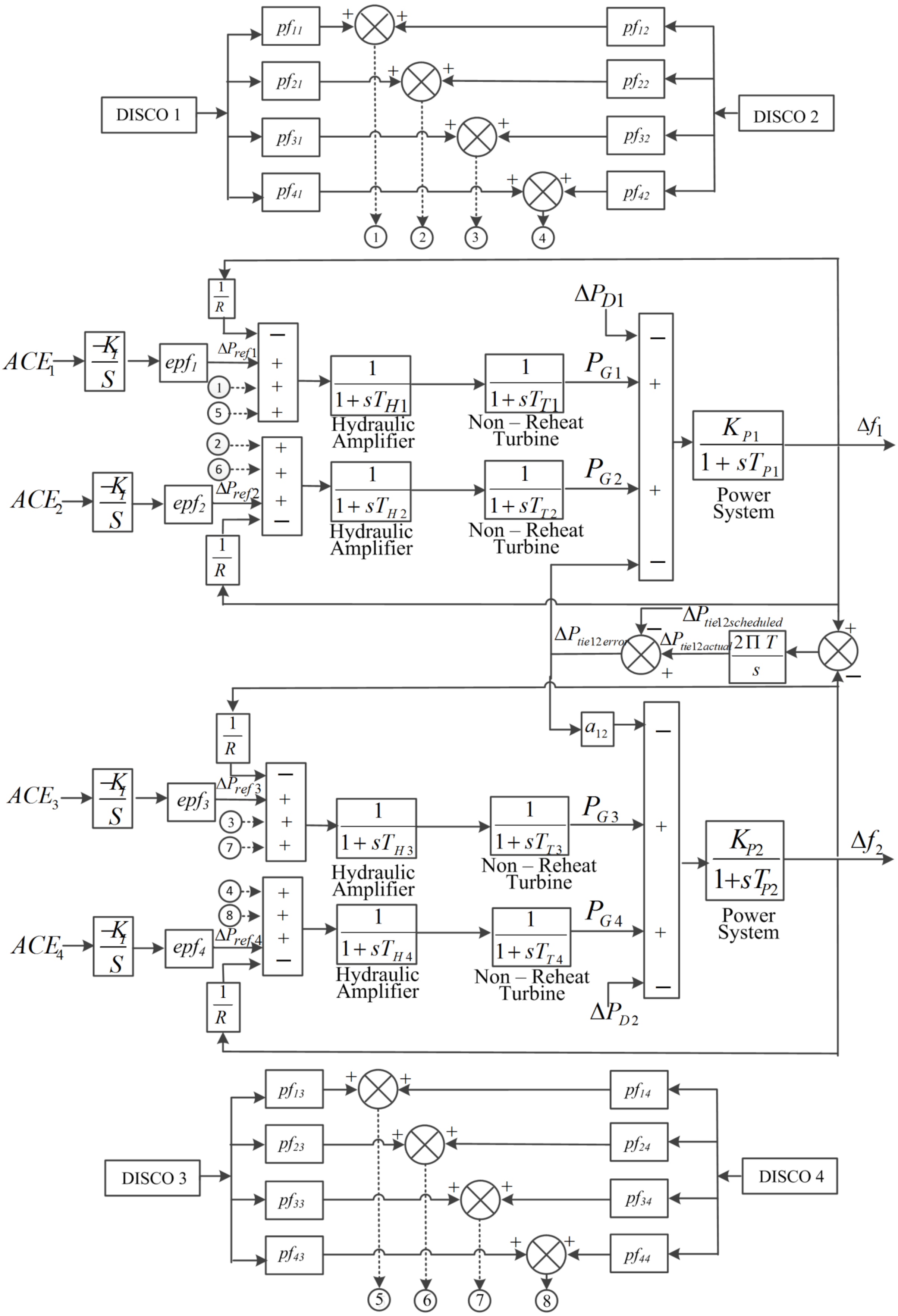


**Fig. 1.Mathematical model of two area restructured power system.**

In order to regulate frequency during violation, frequency variation (*Δf*) is included as input to secondary controller of LFC. For maintaining power through TRANSCO at scheduled value, $\Delta P_{tie12\ error}$ is fed as second input to LFC secondary controller. *Δf* and $\Delta P_{tie12\ error}$ makes Area Control Error (*ACE)*. This forms basis of tie line bias control. When *ACE* is fed to secondary controller, corresponding parameter variations vanish. This means that generation matches with demand and power through TRANSCO maintains at scheduled. In such case, only same area GENCOs with available reserve meet unscheduled demand. Concurrently, tie line bias control does not utilize other area GENCOs and TRANSCO reserve. This contradicts economics. Hence, existing tie line bias control is to be modified to make use of other area GENCOs and TRANSCO reserves.

## IV. PROPOSED LFC STRATEGY

The secondary controller input of LFC under tie line bias control (adopted by all literature), is given in equation (15).

$$\Delta ACE_i = \Delta f_i + \Delta P_{tie\ 12\ error} \quad (15)$$

This makes *Δf* and $\Delta P_{tie\ ij\ error}$ to zero by changing GENCOs output as per equation (16).

$$\Delta P_{Gk} = \begin{cases} epf_k \times \frac{1}{\sum epf_j} \times \Delta P_D & \text{For GENCO 'k' in demand violation area} - j \\ 0 & \text{For GENCO 'i' in another area} - i \end{cases} \quad (16)$$

Where,

$\Delta P_{Gk}$ is change in power generation of the k[th] GENCO

$\sum epf_j$ gives sum of *epf* of GENCOs in area-j where demand violation occurs

Thus, tie line bias control, presently used in deregulated power system, maintains power through TRANSCO at scheduled. Nevertheless, the strategy does not allow TRANSCO to use its extra corridor during violation.

The new proposed strategy replacing tie line bias control, use TRANSCO corridor and at the same time, limits power within maximum during violation. The block diagram representation showing *ACE* input selection in proposed strategy is furnished in Fig. 2.

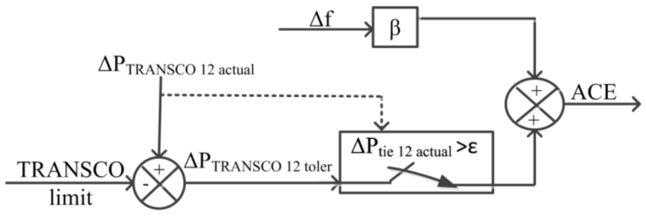


**Fig. 2.ACE input selection strategy.**

During contract, *ACE* does not come into play. However, during violation, if TRANSCO power is within limit, governor operates based on *Δf*. This means that frequency change alone is made to settle at zero but not TRANSCO power variation. Thus, *ACE* of compensating GENCOs is *Δf*, (Fig. 2 with switch open). However, participation of GENCOs in neighbouring area results in increase or decrease in TRANSCO power. Increase in TRANSCO power implies that system uses available TRANSCO reserve. Simultaneously, compensation made by participating GENCOs is based on *epf* value and is as per equation (17).

For any GENCO k in any area,

$$\Delta P_{Gk} = epf_k \times \Delta P_D \quad (17)$$

Where,

$P_D$ represents unscheduled demand

$epf_k$ is the *epf* of k[th] GENCO

Nevertheless, governor should not let TRANSCO power to increase beyond maximum. This means that in addition to bring frequency variation to zero, TRANSCO power must be set to maximum limit. This is possible when *ACE* becomes *Δf* +$\Delta P_{tie\ 12\ toler}$ (Fig. 2 with switch closed). This allows use of TRANSCO corridor only up to its maximum limits and makes frequency change to zero. The changes in GENCO power is as per equation (18).

$$\Delta P_{Gk} = \begin{cases} epf_k \times \frac{1}{\sum epf_i} \times (\Delta P_D - \Delta P_{ptie\ 12\ toler}) & \text{For GENCO 'k' in violated area i} \\ epf_k \times \frac{1}{\sum epf_j} \times \Delta P_{ptie\ 12\ toler} & \text{For GENCO 'k' in neighbouring area j} \end{cases} \quad (18)$$

Once, TRANSCO limit is reached, the switch is closed, allowing LFC to operate under tie line bias strategy, making same area GENCOs to meet remaining unscheduled power.

## V. RESULTS AND DICUSSIONS

The mathematical model of system shown in Fig. 1 is simulated using system parameters furnished in Nomenclature. The following sections analyse each model for two different violations; one which results in TRANSCO power within limit, while other creates TRANSCO line congestion. The performance of proposed strategy under violations is compared with tie line bias control.

### A. Performance analysis of proposed strategy under bilateral model

For two area system operating under bilateral model, DISCO1 through DISCO4 demands power of 0.1p.u., 0.05p.u., 0.2p.u. and 0.1p.u. respectively. The participation of GENCO for demands made by DISCOs is given in equation (19).

$$DPM = \begin{bmatrix} 0.4 & 0.1 & 0.1 & 0.4 \\ 0.3 & 0.2 & 0.2 & 0.3 \\ 0.2 & 0.3 & 0.3 & 0.2 \\ 0.1 & 0.4 & 0.4 & 0.1 \end{bmatrix} \quad (19)$$

The power contributed by GENCO, calculated using equation (2) is given in Table I.

**Table- I: GENCOs contracted powers under bilateral model**

| | DISCO 1 | DISCO 2 | DISCO 3 | DISCO 4 | Total |
|---|---|---|---|---|---|
| **GENCO1** | 0.04 | 0.005 | 0.02 | 0.04 | 0.105 |
| **GENCO2** | 0.03 | 0.01 | 0.04 | 0.03 | 0.11 |
| **GENCO3** | 0.02 | 0.015 | 0.06 | 0.02 | 0.115 |
| **GENCO4** | 0.01 | 0.02 | 0.08 | 0.01 | 0.12 |

From Table I it is clear that GENCOs in area-1 meet 0.085p.u. and 0.13p.u. demands of DISCOs in area-1 and area-2 respectively. Similarly, area-2 GENCOs meet 0.17p.u. and 0.065p.u. area-2 and area-1 DISCOs. Therefore, scheduled TRANSCO power from area-1 to area-2 is **0.065**(i.e.,0.13–0.065)**p.u.**. Considering 0.07p.u. TRANSCO limit, there is an extra corridor of 0.005p.u..

The mathematical model under bilateral model, adopting tie line bias and proposed strategy is subjected to violations of 0.009p.u. and 0.011p.u. at 200s and 300s respectively in area-2. Under bilateral model, GENCO1, GENCO2, GENCO3 and GENCO4 make a contract to meet the unscheduled power by 20%, 30%, 40% and 10%. Thus, *epf* becomes 0.2, 0.3, 0.4 and 0.1 for GENCO1 through 4 respectively. When system is under tie line bias control, only same area GENCOs does compensation to maintain TRANSCO power. The GENCOs and TRANSCO powers under tie line bias control for these violations are shown in Fig. 3(a) and Fig. 3(c).

When system is under GENCO and TRANSCO reserve based strategy, area-1 GENCOs contribute 50% of total violation. Thus, area-1 GENCOs increase generation by 0.0045p.u.. This makes TRANSCO power increase to 0.0695p.u., which is within TRANSCO limit (0.07p.u.). Thus, according to strategy explained using Fig. 2, $\Delta f$ serves as input to *ACE*. This makes TRANSCO power to vary from scheduled value, hence allows GENCOs in area-1 to compensate for unscheduled power. However, with violation of 0.011p.u. and same *epf*, TRANSCO power exceeds its capacity. This makes *ACE* equal to $\Delta f+\Delta P_{tie\ 12\ toler}$. Hence, the strategy restricts TRANSCO power limit to 0.07p.u., in addition to change in system frequency. This makes area-1 and area-2 GENCOs to increase generation by 0.005p.u with ratio 0.2:0.3 and by 0.006p.u. with ratio 0.4:0.1 respectively. The GENCOs and TRANSCO power responses under the proposed strategy for this condition are shown in Fig. 3(b) and Fig. 3(c).

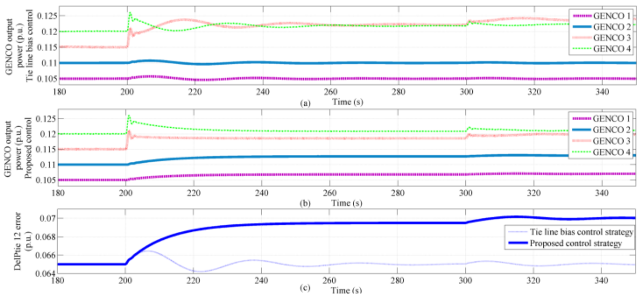


**Fig. 3.GENCOs and TRANSCO responses incorporating different strategies under bilateral model for violations of 0.009p.u. at 200s and 0.011p.u. at 300s in area-2.**

The GENCOs and TRANSCO powers during contract (till 200s) in Fig. 3(a) and Fig. 3(b), match with values in Table I. Fig. 3(a) shows that incorporating tie line bias control, during violation of 0.009p.u. (200s–300s), output of GENCO3 and GENCO4 are increased from **0.115p.u.** to **0.1222p.u.** and from **0.12p.u.** to **0.1218p.u.** respectively. The neighbouring area GENCOs do not contribute for the violated demand. Thus tie line power remains unaltered.

Also, during violation of 0.011p.u. (from 300s), output of GENCO3 and GENCO4 are increased to **0.1238p.u.** and **0.1222p.u.** from **0.1222p.u.** and **0.1218p.u.** respectively. Whereas, GENCO1 and GENCO2 do not participate in LFC. The tie line bias control maintains TRANSCO power equal to **0.065p.u.**. This is seen from Fig. 3(c).

However, during violation of 0.011p.u. (200s–300s), the proposed strategy (Fig. 3(b)), increase power of GENCO1 from **0.105p.u.** to **0.1068p.u.**, GENCO2 from **0.11p.u.** to **0.1127p.u.**, GENCO3 from **0.115p.u.** to **0.1186p.u.**, GENCO4 from **0.12p.u.** to **0.1209p.u.**. Fig. 3(b) also proves that the proposed strategy allows use of TRANSCO reserve and hence TRANSCO power is increased from **0.065p.u.** to **0.0695p.u.**.

During violation of 0.011p.u. (from 300s), output of GENCO1 through GENCO4 increases from **0.1068p.u.**, **0.1127p.u.**, **0.1186p.u.** and **0.1209p.u.** to **0.107p.u.**, **0.113p.u.**, **0.1198p.u.**, and **0.1212p.u.** respectively. However, this makes TRANSCO power to exceed limit and thus proposed strategy limits it to **0.07p.u.**. This is clear from Fig. 3(c).

A better comparison between proposed and tie line bias control performances under bilateral model for violations of 0.009p.u. and 0.011p.u is presented in Fig. 4 (a) and Fig. 4 (b) respectively.

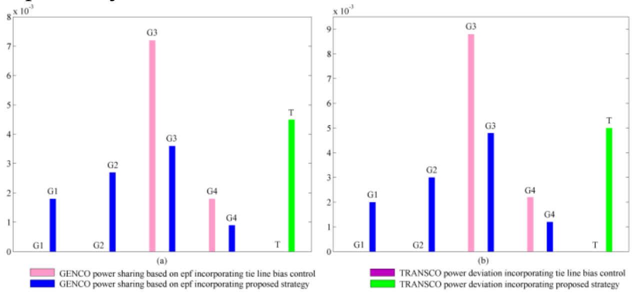


**Fig. 4.Comparison of performance of proposed with tie line bias control under bilateral model.**

Fig. 4(a) shows power increase in GENCOs and TRANSCO incorporating tie line bias control and proposed control during violation of 0.009p.u. in area 2. Fig. 4 clearly shows that tie line bias control does not allow GENCO1(G1), GENCO2(G2) to contribute for demand violation, thus not making use of TRANSCO reserve. However, the proposed strategy operates as per economic factor, allowing more economic GENCOs in neighbouring area to participate for meeting the violated demand.

Fig. 4(b) presents GENCOs and TRANSCO power increase incorporating tie line bias control and proposed control during violation of 0.011p.u. in area 2. It is evident from figure that tie line bias control allows only GENCO3(G3) and GENCO4(G4) to contribute for violation. Conversely, the proposed strategy allows neighbouring area GENCOs that are more economical to contribute for violated demand, making use of TRANSCO reserve, while limiting power to its capacity.

### B. Performance analysis of proposed strategy under poolco model

For the considered system under poolco model, area-1 and area-2 demands 0.3p.u. and 0.15p.u. respectively. The participation of each GENCO to meet area demands is decided by the pool operator from the allotted power obtained at the end of auction mechanism. The contract decision procedure is explained in detail in [27]. Using this procedure, the APM obtained for two areas are given in equation (20) – (21).

$$APM_1 = \begin{bmatrix} 0.7 & 0.22 \\ 0.3 & 0.2 \end{bmatrix} \quad (20)$$

$$APM_2 = \begin{bmatrix} 0 & 0.33 \\ 0 & 0.25 \end{bmatrix} \quad (21)$$

The contracted power calculated using equation (7) is given in Table II.

**Table- II: GENCOs contracted powers under poolco model**

| | Area-1 | Area-2 | Total |
|---|---|---|---|
| **GENCO1** | 0.21 | 0.033 | 0.243 |
| **GENCO2** | 0.09 | 0.03 | 0.12 |
| **GENCO3** | 0 | 0.0495 | 0.0495 |
| **GENCO4** | 0 | 0.0375 | 0.0375 |

Table II shows that 0.3p.u. demand in area-1 is met by same area GENCOs. GENCOs in area-1 and area-2 GENCOs generate 0.063p.u. and 0.087p.u. power respectively, to meet demand in area-2. Thus, 0.063p.u. power flows from area-1. The system is subjected to violations in order to analyse and compare the performance of proposed strategy with tie line bias control. The participation factors of GENCOs are calculated using equation (12) with data given in Appendix and are found to be 0, 0, 0, 1 for tie line bias control and 0.3186, 0.3717, 0, 0.3097 for GENCO and TRANSCO reserve based strategy respectively.

Violations of 0.01015p.u. and 0.02p.u. are created at 300s and 500s respectively in area-2. When the system is under tie line bias control, area-2 willing GENCO, GENCO 4 is made to compensate so as to maintain TRANSCO power at scheduled value. This case is simulated and GENCOs and TRANSCO responses are shown in Fig. 5(a) and Fig. 5(c).

Now, proposed strategy is incorporated in the system and same violations are created in area-2. GENCOs and TRANSCO responses for this case are shown in Fig. 5(b) and Fig. 5(c).

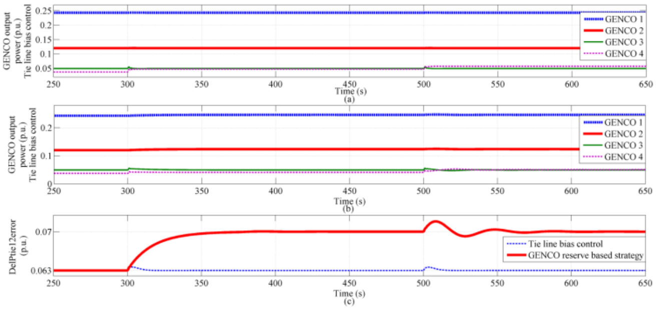


**Fig. 5.GENCOs and TRANSCO responses under poolco model for violation of 0.01015p.u. at 300s and 0.02p.u. at 500s in area-2.**

From Fig. 5(a) and Fig. 5(b), it is seen that GENCO1, through GENCO4 generate contracted power of **0.243p.u.**, **0.12p.u.**, **0.0495p.u.** and **0.0375p.u.** respectively (till 300s). These values well match with those given in Table II. From Fig. 5(a), it is seen that during violation of 0.01015p.u.(300s – 500s), GENCO4 output is increased from 0.0375p.u. to **0.04765p.u.**. The extra power meets unscheduled demand of 0.01015p.u. in area-2. The TRANSCO power remains same as GENCOs in other area do not meet for unscheduled demand.

However, during violation of 0.02p.u. (from 500s), Fig. 5(a) shows that output of GENCO4 is further increased from **0.04765p.u.** to **0.0575p.u.**. At the same time, TRANSCO power remains equal to contract since area-1 GENCOs do not contribute to violated demand and hence, TRANSCO power is same. Thus, it is clear from Fig. 5(a) that tie line bias control reschedules GENCO power so as to maintain TRANSCO power equal to scheduled value.

Replacing tie line bias control with proposed strategy, Fig. 5(b) shows that during violation of 0.01015p.u. in area-2 (300s – 500s), power output of GENCO1, GENCO 2 and GENCO 4 increase from **0.243p.u.**, **0.12p.u.** and **0.0375p.u.** to **0.2462p.u.**, **0.1238p.u.** and **0.04064p.u.** respectively. Area-1 GENCOs contribute to meet **0.006903p.u.** of power to meet un-scheduled power and hence TRANSCO power is increased from **0.063p.u.** to **0.07p.u.**, which is the TRANSCO limit.

However, for a violation of 0.02p.u. (from 500s), Fig. 5(b) shows that only the output of GENCO4 is increased from **0.04064p.u.** to **0.05049p.u.**. From Fig. 5(c) it is clear that the proposed strategy is capable of limiting TRANSCO power to **0.07p.u.** by rescheduling the same area GENCOs.

Comparison of performance between tie line bias control and proposed strategy for violations of 0.01015p.u. and 0.02p.u. is presented in Fig. 6(a) and Fig. 6(b) respectively.

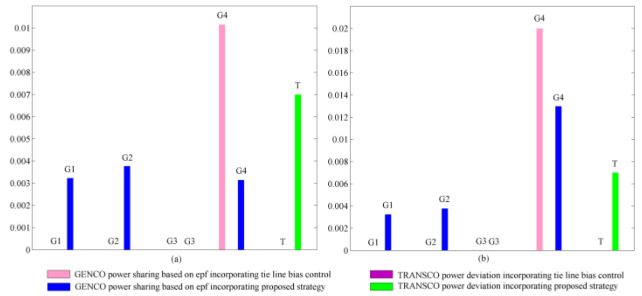


**Fig. 6.Comparison of performance of proposed with tie line bias control under poolco model.**

Fig. 6(a) shows variation in GENCOs and TRANSCO power with tie line bias and proposed strategy respectively under poolco model during violation of 0.01015p.u. in area 2. It is clearly seen from Fig. 6 that tie line bias control does not allow GENCO1(G1) and GENCO2(G2) to contribute for violation in other area. Hence, TRANSCO(T) power change is zero. Whereas, the proposed strategy allows participation of more economic GENCOs in the other area to compensate more for the violated demand, thereby using TRANSCO reserve.

Fig. 6(b) shows power variation in GENCOs and TRANSCO during violation of 0.02p.u. in area 2 under poolco model, incorporating tie line bias control and proposed strategy respectively. It is seen that tie line bias control does not allow GENCO1(G1) and GENCO2(G2) to contribute for demand violation and hence TRANSCO(T) power variation remains zero. This proves that the strategy fails to make use of available TRANSCO reserve. Conversely, the proposed strategy allows all GENCOs and TRANSCO to contribute without exceeding TRANSCO limit (0.07p.u.). This is clear from Fig. 6(b).

The cost incurred in meeting the unscheduled power by willing GENCOs incorporating tie line bias control and GENCO and TRANSCO reserve based strategy is tabulated using data given in Appendix and equation (14) and is given in Table III.

**Table- III: Cost incurred to meet unscheduled demand in Rs/MW**

| | Violation | Strategy | GENCO 1 | GENCO 2 | GENCO 3 | GENCO 4 | Total |
|---|---|---|---|---|---|---|---|
| Bilateral Model | 0.009 p.u. | Tie line bias | 0 | 0 | 9.36 | 8.64 | 18 |
| | | Proposed | 3.6 | 4.05 | 4.68 | 4.32 | 16.65 |
| | 0.011 p.u. | Tie line bias | 0 | 0 | 11.44 | 10.56 | 22 |
| | | Proposed | 4 | 4.5 | 6.24 | 5.76 | 20.5 |
| Poolco Model | 0.01015 p.u. | Tie line bias | 0 | 0 | 0 | 18.27 | 18.27 |
| | | Proposed | 5.66 | 5.66 | 0 | 5.66 | 16.98 |
| | 0.02 p.u. | Tie line bias | 0 | 0 | 0 | 36 | 36 |
| | | Proposed | 5.66 | 5.66 | 0 | 23.39 | 34.7 |

Table III shows that the tie line bias strategy allows only same area GENCOs to meet the unscheduled demand. These GENCOs offer huge price and hence the cost incurred in meeting the unscheduled power demand incorporating this control strategy is high. Conversely, the newly proposed GENCO and TRANSCO reserve based strategy allows GENCOs in the neighbouring area that offers less price, in addition to same area GENCOs, to meet the violated demand till the TRANSCO limit. This reduces the incurred cost compared to that with tie line bias control. This is clear from Table III. This proves that the proposed strategy is in accordance with the concept of "profiting from innovations [29]" and supports the aim of maximising social welfare.

## VI. CONCLUSION

The paper analyzes the participation of each GENCO in two area power system under bilateral and poolco model incorporating tie line bias control and proposed TRANSCO reserve based strategy for various violations. The contract violation in a multi area deregulated system is met by willing GENCOs and is based on the economic factor. This factor is decided from the offered price of willing GENCOs. Adopting tie line bias control gives priority in maintaining TRANSCO power. This strategy fails to exploit the contribution of other area economic GENCOs. However, the proposed strategy qualifies economic GENCOs in any area to contribute for violated demand using TRANSCO reserve up to the maximum limit. When violation congests TRANSCO line, this scheme maintains TRANSCO power at maximum capacity by compromising economic GENCOs contribution from other area. The comparison results prove effective performance of proposed TRANSCO reserve based control strategy over the existing tie line bias control. The proposed strategy is effective in allowing neighbouring GENCOs with less offered price compared to same area GENCOs. The comparison also shows that the cost incurred incorporating GENCO and TRANSCO reserve based strategy is less than that with tie line bias control that proves the efficient operation of the new strategy.

## NOMENCLATURE

| | |
|---|---|
| $ACE_i$ | Area Control Error of $i^{th}$ GENCO area; p.u. |
| $\Delta f_k$ | Change in frequency in $k^{th}$ area; Hz |
| $\Delta P_{Gi}$ | Change in power output of $i^{th}$ GENCO; p.u. |
| $\Delta P_{Dk}$ | Change in demand in $k^{th}$ area; p.u. |
| $\Delta P_{refi}$ | Change in reference setting of $i^{th}$ GENCO; p.u. |
| $P_{Lj}$ | Local load of $j^{th}$ DISCO; p.u. |
| $a_{12}$ | Control area capacity factor |
| $T_{Hi}$ | Time constant of $i^{th}$ hydraulic amplifier; 0.08s |
| $T_{Ti}$ | Time constant of $i^{th}$ turbine; 0.3s |
| $K_{Pk}$ | Gain of $k^{th}$ area; 100 |
| $T_{Pk}$ | Time constant of $k^{th}$ area; 20s |
| $R_i$ | Droop characteristics of $i^{th}$ GENCO; 2Hz/p.u. |
| $\beta$ | Area frequency response characteristics; p.u./Hz |
| $K_I$ | Gain of integral controller |
| $cpf_{ij}$ | Contract participation factor of $i^{th}$ GENCO on $j^{th}$ DISCO |
| $epf_i$ | Economic participation factor of $i^{th}$ GENCO |
| $\Delta P_{tie\ 12\ scheduled}$ | Scheduled tie line power deviation; p.u. |
| $\Delta P_{tie\ 12\ actual}$ | Actual tie line power deviation; p.u. |
| $\Delta P_{tie\ 12\ error}$ | Error in tie line power deviation; p.u. |
| T | Synchronizing coefficient; 0.444 |

## APPENDIX

GENCO offers for contract violation under bilateral model

| GENCO | $G_{11}$ | $G_{21}$ | $G_{12}$ | $G_{22}$ |
|---|---|---|---|---|
| $Price_{off-un}$ (Rs/MW) | 2000 | 1500 | 1300 | 4800 |

GENCO offers for contract violation under poolco model

| GENCO | $G_{11}$ | $G_{21}$ | $G_{22}$ |
|---|---|---|---|
| $Price_{off-un}$ (Rs/MW) | 1750 | 1500 | 1800 |

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