# Congestion Mitigation based on Generator Sensitivities in Deregulation

*T. Nireekshana , Dr.G.Kesava Rao and Dr.S.Siva Naga Raju*

***Abstract*-Power system congestion is a main problem that the independent system operator (ISO) would face in the post-deregulated era. One of the most practiced and an obvious technique of congestion management is rescheduling the generators output power in the system. However, all generators in the system will not participate in congestion. Development of sound formulation and appropriate solution technique for this problem is aimed in this paper. Contributions made in the present paper are twofold. Firstly a technique for optimum selection of participating generators has been introduced using generator sensitivities to the power flow on congested lines. Secondly this paper proposes an algorithm based on arbitrary method which minimizes the deviations of rescheduled values of generator power outputs from scheduled levels.The suggested methodology is tested on few test cases like 6-bus system, IEEE 14-bus system, and also on IEEE 30-bus system which gives the best results in all the cases.**

**Index Terms—Independent System Operator (ISO), Deregulation, Generator Sensitivity, Power world Simulator, Rescheduling.**

## I. INTRODUCTION

Deregulated power system means Transmission companies (TRANSCO's), Generation companies (GENCO's) and Distribution Companies (DISCO's) are under different organizations. Organizations can fix their own prices. To maintain coordination between them there will be independent system operator(ISO) in all types of deregulated power system models [1-4]. In this market GENCO's and DISCO's submit the sell and purchase decisions in the form of bids to the market operator in hourly price manner. Finally 24 hour energy prices to be paid by consumers and to be charged by producers.

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NEED FOR AN INDEPENDENT SYSTEM OPERATOR (ISO)

With unbundling of generation from transmission sector in a competitive market, generation sector will be become fully competitive with many market participants whereas the transmission system remains regulated monopoly and it will be necessary to provide non-discriminatory and open access to all the market participants through planning and operation of power transmission system. It is also important to ensure reliability of the network in its region of operation. This function can be implemented by entity called Independent System Operator (ISO).

In deregulated power systems, ISO dispatches the generators so that to meet the demand of loads at the minimum cost while maintaining security and service quality of power system.ISO compute LMPs by running optimal power flow.

Bidding process for a specified period, e.g. next two hours, is as below.

• Every producer submits the following values to ISO:

Minimum and maximum power which can deliver to the network

Bid price for selling 1 MW electric power

• Every consumer submits the following values to ISO:

Minimum and maximum load demand

Load bid for load curtailment in emergency condition (if LMP of a load exceeds its bid then the load is curtailed till its LMP reduces to its bid)

• ISO run the optimal power flow and computes the following values:

MW dispatch of each generator

MW dispatch of each load

LMP of each bus

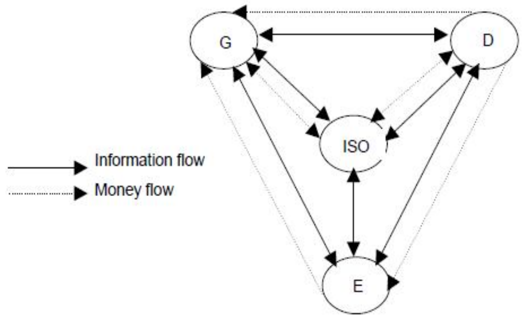


Figure1: ISO importance

With increasing demand for electric power all around the globe, electric utilities have been forced to meet the increasing demand by increasing their generation. However, the electric power that can be transmitted between two locations on a transmission network is limited by several transfer limits such as thermal limits, voltage limits and stability limits with the most restrictive applying at a given time. If the transmission line overcomes these limits, then the line is said to be “congested”. Transmission networks are the main source of difficulty in deregulation [5,8]. We ensure that the power system operates within its limits is vital to maintain power system security, failing which can result in widespread blackouts with potentially severe social and economic consequences. Congestion management controlling the transmission system power transfer capability is the fundamental transmission management problem.

Congestion or overload in one or more transmission lines of the system may occur as a result of unexpected outages of generation, sudden increase of demand, tripping of transmission lines, or failures of other equipment [12,13,16]. In deregulated power Systems, congestion, which can also occur due to commercial reasons, has become a major concern. Fast, transparent, and effective tools are necessary for congestion management. Power system congestion management is a major problem in deregulated markets because of all the above reasons.

## II. CONGESTION MANAGEMENT METHODS

There are two broad paradigms that may be employed for congestion management. These are the cost-free means and the not-cost-free means. The previous include actions like out aging of congested lines or operation of transformer taps, phase shifters, or FACTS devices. These means are termed as cost-free only because the marginal costs (and not the capital costs) involved in their usage are nominal [14].

The not-cost-free means include:

(1) Rescheduling generation. This leads to generation operation at an equilibrium point away from the one determined by equal incremental costs. Mathematical models of pricing tools may be incorporated in the dispatch framework and the corresponding cost signals obtained. These cost signals may be used for congestion pricing and as indicators to the market participants to rearrange their power injections/extractions such that congestion is avoided.

(2) Prioritization and curtailment of loads/transactions. A parameter termed as willingness-to-pay-to-avoid-curtailment was introduced in. This can be an effective instrument insetting the transaction restriction strategies which may then be incorporated in the optimal power flow framework.

In a congested power line, the incremental or decremented change in power outputs of all the generators do not affect the power transmitted on the congested line to the same extent. Due to this, there is no need to reschedule the outputs of generators whose generations do not affect the congested line flow. We should select the generators whose generation affects the congested line flow. To optimally select the generators participating in congestion management, the sensitivities of the generators to the congested line are used [6, 7]. The generators actually participating in congestion alleviation are chosen based on a criterion which reduces the number of participating generators.

## III. PROBLEM FORMULATION

Based on the bids received from the participant generators, the amount of rescheduling required is computed by solving the following optimization problem:

$$\text{Minimize} \sum_{g}^{Ng} C_g(\Delta P_g)\Delta P_g$$

subject to

$$\sum_{g=1}^{Ng}((\mathrm{GS}_g)\Delta P_g) + F_k^0 \le F_k^{\max} \qquad k = 1, 2 \ldots n_l$$

$$P_g - P_g^{\min} = \Delta P_g^{\min} \le \Delta P_g \le \Delta P_g^{\max} = P_g^{\max} - P_g \qquad g = 1, 2, \ldots N_g$$

$$\sum_{g=1}^{N_g} \Delta P_g = 0$$

Where $\Delta P_g$ is the real power adjustment at bus-g and $C_g$ are the incremental and decremented price bids submitted by generators? These are the prices at which the generators are willing to adjust their real power outputs. $F_k^0$ is the power flow caused by all contracts requesting the transmission service. $F_k^{\max}$ is the line flow limit of the line connecting bus-i and bus-j.

$N_g$ is the number of participating generators, $n_1$ is the number of transmission lines in the system, $P_g^{\min}$ and $P_g^{\max}$ denote respectively the minimum and maximum limits of generator outputs. It can be seen that the power flow solutions are not required during the process of optimization. .

## IV. CALCULATION OF GENERATOR SENSITIVITY

The generators in the system have different sensitivities to the power flow on the congested line.

GENERATOR SENSITIVITY:

A change in real power flow in a transmission line k connected between bus i and bus j due to change in power generation by generator g can be termed as generator sensitivity to congested

line (GS).

$$\text{GS}_g = \frac{\Delta P_{ij}}{\Delta P_{G_g}}$$

Where $P_{ij}$ is the real power flow on congested line-k;$P_{Gg}$ is the real power generated by the $g^{th}$ generator. Basic power flow equation on congested line can be written as

$$P_{ij} = -V_i^2 G_{ij} + V_i V_j G_{ij} \cos(\theta_i - \theta_j) + V_i V_j B_{ij} \sin(\theta_i - \theta_j)$$

Where $V_i$ and $\theta_i$ are the voltage magnitude and phase angle respectively at the ith bus; Gij and $B_{ij}$ represent, respectively, the conductance and susceptance of the line connected between buses i and j.

$$\text{GS}_g = \frac{\partial P_{ij}}{\partial \theta_i} \cdot \frac{\partial \theta_i}{\partial P_{G_g}} + \frac{\partial P_{ij}}{\partial \theta_j} \cdot \frac{\partial \theta_j}{\partial P_{G_g}}$$

$$\frac{\partial P_{ij}}{\partial \theta_i} = -V_i V_j G_{ij} \sin(\theta_i - \theta_j) + V_i V_j B_{ij} \cos(\theta_i - \theta_j)$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = +V_i V_j G_{ij} \sin(\theta_i - \theta_j) - V_i V_j B_{ij} \cos(\theta_i - \theta_j) = -\frac{\partial P_{ij}}{\partial \theta_i}.$$

The active power injected at a bus-s can be represented as

$$P_s = P_{G_s} - P_{D_s}$$

Where $P_{Ds}$ is the active load at bus-s .$P_s$ can be expressed as

$$\begin{aligned} P_s &= |V_s| \sum_{t=1}^{n} ((G_{st} \cos(\theta_s - \theta_t) + B_{st} \sin(\theta_s - \theta_t))|V_t|) \\ &= |V_s|^2 G_{ss} + |V_s| \sum_{\substack{t=1 \\ t \neq s}}^{n} \{(G_{st} \cos(\theta_s - \theta_t) + B_{st} \sin(\theta_s - \theta_t))|V_t|\} \end{aligned}$$

Where n is the number of buses in the system. Differentiating above equation w.r.t.$\theta_t$ and ,$\theta_s$ the following relations can be obtained

$$\frac{\partial P_s}{\partial \theta_t} = |V_s||V_t|\{G_{st} \sin(\theta_s - \theta_t) - B_{st} \cos(\theta_s - \theta_t)\}$$

$$\frac{\partial P_s}{\partial \theta_s} = |V_s| \sum_{\substack{t=1 \\ t \neq s}}^{n} \{(-G_{st} \sin(\theta_s - \theta_t) + B_{st} \cos(\theta_s - \theta_t))|V_t|\}.$$

Neglecting P-V coupling, the relation between incremental change in active power at system buses and the phase angles of voltages can be written in matrix form as

$$\underset{n\times 1}{[\Delta P]} = \underset{\text{n}\times\text{n}}{[H]} \underset{n\times 1}{[\Delta \theta]}$$

$$\underset{\text{n}\times\text{n}}{[H]} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial \theta_2} & \cdots & \frac{\partial P_1}{\partial \theta_n} \\ \frac{\partial P_2}{\partial \theta_1} & \frac{\partial P_2}{\partial \theta_2} & & \frac{\partial P_2}{\partial \theta_n} \\ \vdots & & & \vdots \\ \frac{\partial P_n}{\partial \theta_1} & \frac{\partial P_n}{\partial \theta_2} & \cdots & \frac{\partial P_n}{\partial \theta_n} \end{bmatrix}_{\text{n}\times\text{n}}$$

$$\begin{aligned} [\Delta \theta] &= [H]^{-1}[\Delta P] \\ &= [M][\Delta P] \end{aligned}$$

$$[M] = [H]^{-1}.$$

To find the values of $(\partial \theta_i)/(\partial P_{G_g})$ and $(\partial \theta_j)/(\partial P_{G_g})$ in (5), $[M]$ needs to be found out. However, $[H]$ is a singular matrix of rank one deficiency? So it is not directly invertible. The slack bus in the present work has been considered as the reference node and assigned as bus number 1. The elements of first row and first column of $[H]$ can be eliminated to obtain a matrix $[H_{-1}]$ which can be inverted to obtain matrix $[M_{-1}]$, where $(\cdot)_{-1}$ represents a matrix with its first row and column deleted or a vector with the first element deleted. Using these relations the following equation can be obtained.

$$[\Delta \theta_{-1}] = [M_{-1}][\Delta P_{-1}].$$

The actual vector $[\Delta \theta]$ can be found by simply adding the element $\Delta \theta_1$ to the above equation as shown by the following relation.

$$\underset{n\times 1}{[\Delta \theta]} = \underset{n\times n}{\begin{bmatrix} 0 & 0 \\ 0 & [M_{-1}] \end{bmatrix}} \underset{n\times 1}{[\Delta P]} + \Delta \theta_1 \underset{n\times 1}{\begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}}.$$

The second term of the above equation vanishes as change in phase angle of slack bus is zero. Accordingly it reduces to

$$\underset{n\times 1}{[\Delta\theta]} = \underset{\mathrm{n}\times\mathrm{n}}{\begin{bmatrix} 0 & 0 \\ 0 & [M_{-1}] \end{bmatrix}} \underset{n\times 1}{[\Delta P]}.$$

Thus required elements of $(\partial\theta_i)/(\partial P_{G_g})$ and $(\partial\theta_j)/(\partial P_{G_g})$ are found out from above equation.

It is to be noted that the generator sensitivity values thus obtained are with respect to the slack bus as the reference. So the sensitivity of the slack bus generator to any congested line in the system is always zero.

$GS_g$ denotes how much active power flow over a transmission line connecting bus-i and bus-j would change due to active power injection by generator g. The system operator selects the generators having non uniform and large magnitudes of sensitivity values as the ones most sensitive to the power flow on the congested line and to participate in congestion management by rescheduling their power outputs [9-11].

Based on the bids received from the participant generators, the amount of rescheduling required is computed by solving the following optimization problem.

## V. TEST CASES & RESULTS

The proposed method is done by using power world simulator 8.0 [17] for the best results as follows.

### *6- BUS SYSTEM*

#### *Case 1: WHEN CONGESTION IN LINE (4-6)*

Line 4-6 is congested by 101% as shown in figure 2 and it is relieved by rescheduling the generation of participating generators in congestion as follows.

**SENSITIVITIES OF GENERATORS FOR CONGESTED LINE (4-6):**

Table1: Sensitivities of generators to congested line (4-6)

| ***Gen. No.*** | ***1*** | ***2*** | ***3*** | ***4*** |
|---|---|---|---|---|
| ***Sensitivity*** | ***0*** | ***0.0647*** | ***-0.342*** | ***0.13*** |

Based on sensitivities of generators, the generators G1, G2, G3, and G4 are the participating generators for congestion in line 4-6 as shown in table1.

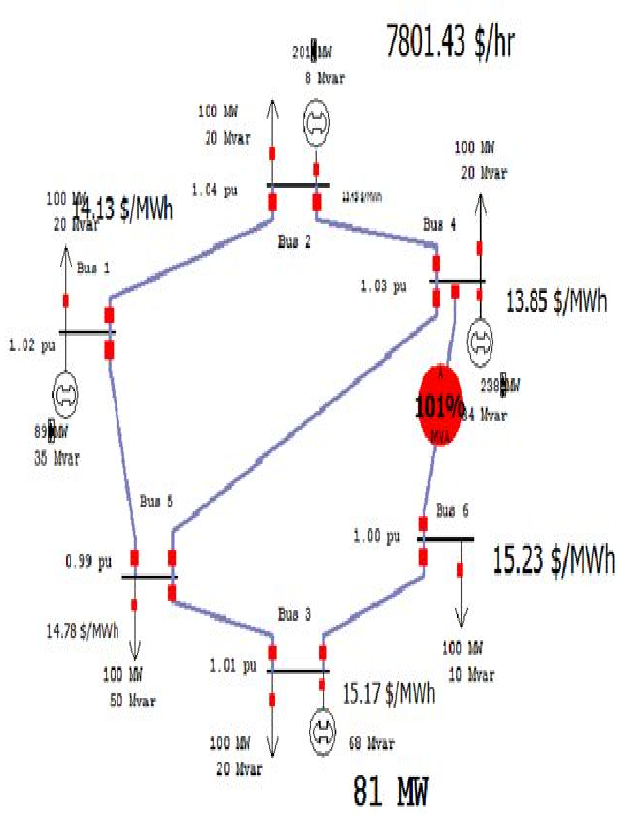


Figure 2: single line diagram of 6-Bus system (congestion case)

**RESCHEDULE OF GENERATION 6-BUS SYSTEM**:

Table 2: Reschedule of Generation in 6-Bus system

| ***S NO*** | ***GEN 1(MW)*** | ***GEN2 (MW)*** | ***GEN 3(MW)*** | ***GEN4 (MW)*** | ***TOTAL COST($/MW)*** | ***% LOADING IN 4-6 LINE*** |
|---|---|---|---|---|---|---|
| ***1*** | ***88.9*** | ***201.2*** | ***81*** | ***238*** | ***7801.43*** | ***101*** |
| ***2*** | ***88.9*** | ***202*** | ***89*** | ***230*** | ***7801.34*** | ***99*** |
| ***3*** | ***92*** | ***204*** | ***84*** | ***230*** | ***7798.93*** | ***99*** |
| ***4*** | ***96*** | ***205*** | ***88*** | ***220*** | ***7804*** | ***96*** |
| ***5*** | ***101*** | ***205*** | ***84*** | ***220*** | ***7806.03*** | ***98*** |
| ***6*** | ***106*** | ***200*** | ***84*** | ***220*** | ***7807.70*** | ***97*** |
| ***7*** | ***106*** | ***200*** | ***94*** | ***210*** | ***7815.53*** | ***93*** |
| ***8*** | ***87*** | ***203*** | ***89*** | ***230*** | ***7801.5*** | ***97*** |
| ***9*** | ***77*** | ***204*** | ***89*** | ***239*** | ***7803.02*** | ***99*** |

Based on sensitivity of generators four generators are rescheduled their generation which should satisfy the objective function as minimization of cost and minimization of congestion. The optimal rescheduling for this case is G1 92MW, G2 204MW, G3 84MW, G4 230MW and then the cost is 7798.93 $/MW and $P_{4\text{-}6}$ is 99% as shown in table 2. The congestion in line 4-6 is relieved from 101% to 99% as shown in figure 3.

***Case 2: WHEN CONGESTION RELIEVED IN LINE (4-6):***

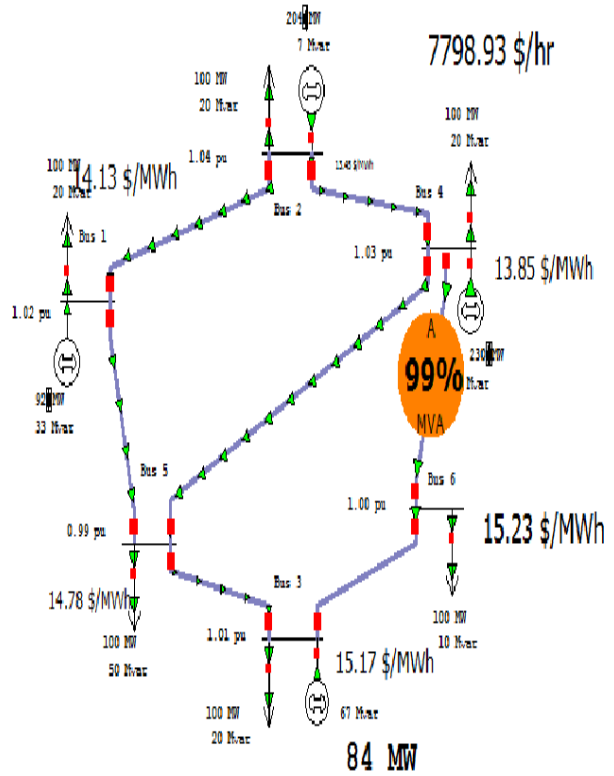


Figure 3: single line diagram of 6-Bus system (congestion relief case)

***14- BUS SYSTEM***

***Case 1: When Congested line is 7-9:***

Line 7-9 is congested by 104% as shown in figure 4 and it is relieved by rescheduling the generation of participating generators in congestion as follows.

SENSITIVITIES OF GENERATORs TO CONGESTED LINE (7-9):

Table 3: Sensitivities of generators to congested line (7-9)

| ***Gen. No.*** | ***1*** | ***2*** | ***3*** | ***6*** | ***8*** |
|---|---|---|---|---|---|
| ***Sensitivity*** | ***0*** | ***-0.0018*** | ***0.0036*** | ***-0.21*** | ***0.3281*** |

Based on sensitivities of generators, the generators G1, G2, G3, G6 and G8 are the participating generators for congestion in line 7-9 as shown in table 3.

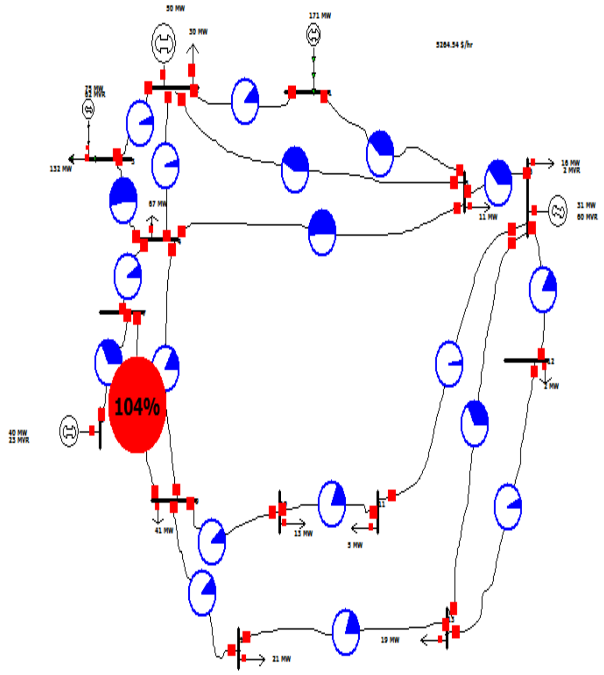


Figure 4: single line diagram of 14-Bus system (congested case)

RESCHEDULING OF GENERATORS TO CONGESTED LINE (7-9):

Table 4: Rescheduling of generators for congested line 7-9

| ***S NO*** | ***GEN1 (MW)*** | ***GEN2 (MW)*** | ***GEN3 (MW)*** | ***GEN6 (MW)*** | ***GEN8 (MW)*** | ***TOTAL COST*** | ***%LOADING ON 7-9 LINE*** |
|---|---|---|---|---|---|---|---|
| ***1*** | ***171*** | ***50*** | ***75*** | ***31*** | ***40*** | ***5264.54*** | ***104*** |
| ***2*** | ***171*** | ***50*** | ***75*** | ***51*** | ***20*** | ***5263.20*** | ***87*** |
| ***3*** | ***161*** | ***50*** | ***75*** | ***61*** | ***20*** | ***5257.18*** | ***84*** |
| ***4*** | ***151*** | ***60*** | ***75*** | ***61*** | ***20*** | ***5370.07*** | ***85*** |
| ***5*** | ***161*** | ***60*** | ***65*** | ***61*** | ***20*** | ***5256.93*** | ***86*** |
| ***6*** | ***151*** | ***50*** | ***75*** | ***61*** | ***30*** | ***5232.41*** | ***90*** |
| ***7*** | ***151*** | ***40*** | ***75*** | ***71*** | ***30*** | ***5146.41*** | ***90*** |
| ***8*** | ***151*** | ***30*** | ***75*** | ***81*** | ***30*** | ***5111.10*** | ***85*** |
| ***9*** | ***141*** | ***40*** | ***75*** | ***81*** | ***30*** | ***5189.36*** | ***90*** |
| ***10*** | ***145*** | ***51*** | ***83*** | ***45*** | ***40*** | ***5347.55*** | ***100*** |

Based on sensitivity of generators four generators are rescheduled their generation which should satisfy the objective function as minimization of cost and minimization of congestion. The optimal rescheduling for this case is G1

151MW, G2 30MW, G3 75MW, G6 81MW, G8 30MW and then the cost is 5111.10 $/MW and $P_{7\text{-}9}$ is 85% as shown in table 2.4. The congestion in line 7-9 is relieved from 104% to 85% as shown in figure 5.

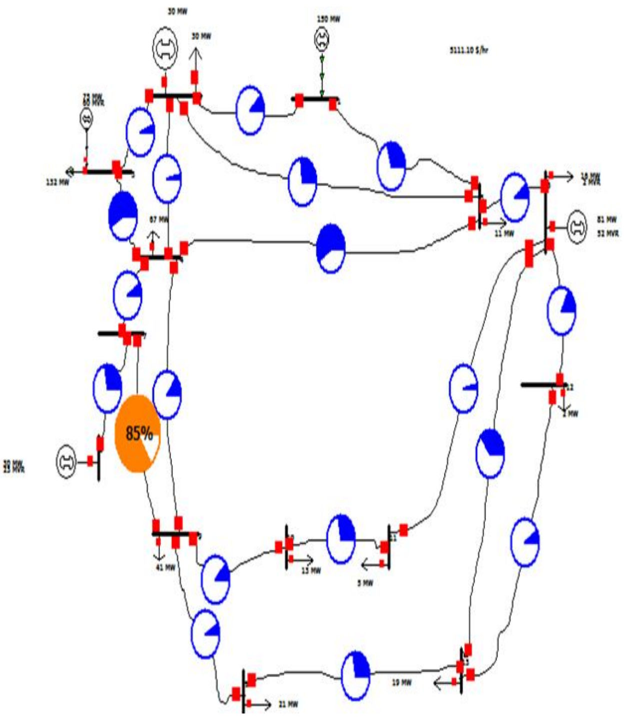


Figure 5: Single line diagram of 14- bus system (congestion relief case)

### *30-BUS SYSTEM*

#### *Case 1: When congested line is 12-13*

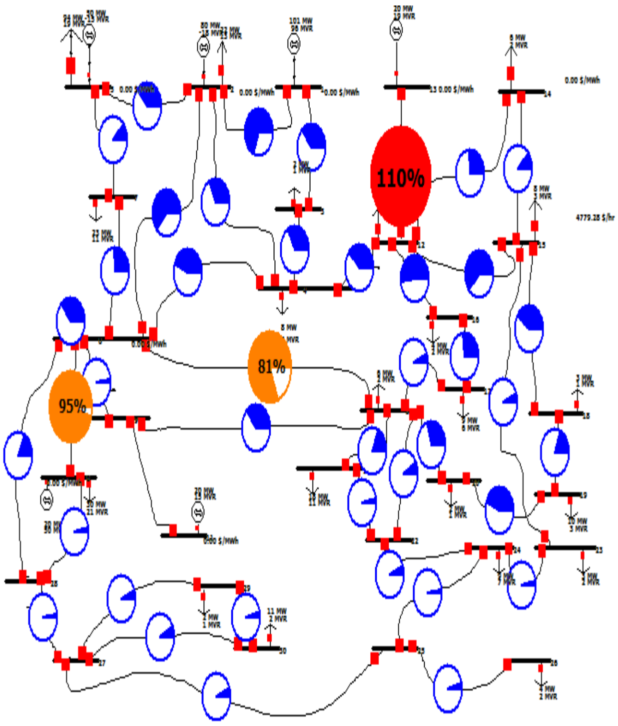


Figure 6: Single line diagram of 30-Bus system

Line 12-13 is congested by 110% as shown in figure 6 and it is relieved by rescheduling the generation of participating generators in congestion as follows.

**SENSITIVITY OF GENERATORS TO CONGESTED LINE 12-13:**

Table 5: Sensitivities of generators to congested line 12-13

| *Gen. No.* | *1* | *2* | *5* | *8* | *11* | *13* |
|---|---|---|---|---|---|---|
| *Sensitivity* | *0* | *0* | *0* | *0* | *1.01* | *-1.09* |

Based on sensitivities of generators, the generators G1, G2, G5, G8 and G13 are the participating generators for congestion in line 12-13 as shown in table 5.

**RESCHEDULING OF GENERATORS:**

Table 6: Rescheduling of 30- Bus system for line 12-13

| *S NO* | *GEN 1* | *GEN 2* | *GEN 5* | *GEN 8* | *GEN 11* | *GEN 13* | *TOTAL COST($/MW)* |
|---|---|---|---|---|---|---|---|
| *1* | *101* | *80* | *50* | *20* | *20* | *20* | *4779.28* |
| *2* | *110* | *80* | *50* | *20* | *20* | *11* | *4749.58* |
| *3* | *120* | *70* | *50* | *20* | *20* | *11* | *4801.97* |
| *4* | *120* | *80* | *40* | *20* | *20* | *11* | *4208.97* |
| *5* | *120* | *90* | *30* | *20* | *20* | *21* | *3937.79* |
| *6* | *120* | *90* | *30* | *24* | *20* | *17* | *3923.59* |
| *7* | *120* | *90* | *30* | *26* | *20* | *15* | *3924.7* |
| *8* | *122* | *90* | *20* | *26* | *30* | *15* | *3740.07* |
| *9* | *111* | *81* | *20* | *35* | *30* | *15* | *3764.83* |
| *10* | *112* | *80* | *20* | *35* | *30* | *15* | *3769.48* |
| *11* | *82* | *80* | *50* | *15* | *35* | *30* | *4782.52* |

Based on sensitivity of generators four generators are rescheduled their generation which should satisfy the objective function as minimization of cost and minimization of congestion. The optimal rescheduling for this case is G1 122MW, G2 90MW, G5 20MW, G8 26MW, G11 30MW, G13 15MW and then the cost is 3740.07 $/MW and $P_{7\text{-}9}$ is 96% as shown in table 6. The congestion in line 12-13 is relieved from 110% to 96%.

## VI. CONCLUSION

This paper gives a method for congestion management in transmission grids using cost-efficient generation rescheduling to minimize the congestion. A realistic frequency and voltage dependent modified fast decoupled load flow method is used with multi objective as minimization of cost and minimization of congestion to solve this complex problem. This method also provides a set of Pareto optimal solutions for any congestion problem, giving the system operator options for judicious decision in solving the congestion.

This paper focuses on demonstrating a technique for optimum selection of generators for congestion management and additionally the application of rescheduling in the solution of the congestion management problem. Generators from the system are selected for congestion management based on their sensitivities to the power flow of the congested line followed by corrective rescheduling. The problem of congestion is modelled as an optimization problem.

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