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# Optimal Power Flow Based Economic Generation Scheduling in Day-ahead Power Market

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**ABSTRACT**

The present work deals with the economic rescheduling of the generation in an hour-ahead electricity market. The schedules of various generators in a power system have been optimizing according to active power demand bids by various load buses. In this work, various aspects of power system such as congestion management, voltage stabilization and loss minimization have also taken into consideration for the achievement of the goal. The Interior Point (IP) based Optimal Power Flow (OPF) methodology has been used to obtain the optimal generation schedule for economic system operation. The IP based OPF methodology has been tested on a modified IEEE-30 bus system. The obtained test results shows that not only the generation cost is reduced also the performance of power system has been improved using proposed methodology.



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## 1. INTRODUCTION

The power system is one of the biggest fields in the area of electricity. This is one of the fields where lots of operational activities have been implemented to further improvement. A power system can be defined as a network of electrical components which are used for the generation, transmission and distribution of electrical power. In the present time scenario the power system has developed as a market which is known as the Power Market. One of the major changes which have come in the power system is its development as an open market. The increase in the demand of electricity with the increasing rate of industrialization and the exponentially increasing rate of urbanization has made the power market a major attraction for the investors. As the market has evolved, more and more investors, public units as well as private units have invested in the power market resulting in the fast evolution of the power market [1-3].

Power generation becomes a more attractive part of system and most of the private investors have shown interest in this part. Power market provides various opportunities for the generation investor. The main objective of these investors is to generate economical power and optimize their respective revenues (profits). Because of number of municipal and private generation participants, profit optimization becomes a challenging task in the power market and also this become more complex due ahead based market operations. Now a day, the power markets have operates on the basis of bidding and auction based mechanism. Normally, these biddings or auctions have based on day-ahead/hour-ahead or minute-ahead based mechanism. The distribution companies have applied the bidding of power on the basis of these mechanisms and the generating companies have supplied the power on the basis of these biddings and system constraints. This mechanism arise an operational problem of scheduling of generators in the system. All the generating companies have tried to get maximum profit by minimum fuel consumption and also fulfill all the operational constraints of the system. This mechanism can provide a solution for revenue increment in the system.

Therefore, an optimal decision has been adopted by the system operators to get an efficient system operation with maximum profit. The Optimal Power Flow (OPF) based rescheduling of generators has frequently used in the market operation to solve the present problem. Many researchers worldwide are working in the area of OPF. Many techniques are developed by researchers to minimize the generation cost in the power system [4].

In the present investigation Interior Point (IP) based OPF technique is used to obtain the optimal rescheduling of generators and minimize the per day total generation cost in a power market. OPF means intelligently adjusting the power system settings in such a way that it manages load flow and at the same time optimizing the operating conditions while fulfilling particular constraints. One another benefit of using the optimal power flow technique is reduces the losses in the system. The problem in the present time scenario is as the power system has emerged as a market, the investors want more profit by injecting and drawing more and more power through the transmission lines without thinking about the capability of the transmission lines which results in the problem of congestion in the transmission system and ultimately resulting in the instability of the whole system. Thus, the OPF based operation has a better opportunity for efficient and secure operation for the power system [5-8].

The present investigation deals with the economic rescheduling of the generation of electricity in an hour-ahead power market. The IEEE-30 bus system is used in this case for the study of the results. In this work, the load buses have applied an hourly based bidding to the system operator and on the basis of these bidding; the generators have scheduled their generations. The optimal schedules of generation have decided using optimization technique. The optimization technique used in this case is the IP method. The IP technique is used for the calculation of OPF of large systems. The result shows the effect of the proposed configuration over the cost of the generated system as well as the effects which occur on the congestion management of the transmission lines and the losses in the system. The cost comparison is done between the results obtained using AC load flow study and OPF based study. The purpose of the present work is to get the better solution for the system which can provide a less costly operation with more congestion free and stable system.

## 2. PROBLEM FORMULATION

Explaining In OPF based solution the main objective is to obtain the minimum generation cost. OPF includes the cost of generators and constraints as variable. The OPF based problem formulation is constituted by three terms; first related with generating cost, second associated with equality constraints and the third term is associated with inequality constraints. The objective function defined as;

$$F(x) = min \sum_{day} \sum_{i=1}^{Ng} C_i(P_{gi}) \quad (1)$$

### 2.1. Equality constraints

$$\sum_{i=1}^{Ng} P_{gi} + \sum_{j=1}^{Nl} P_{di} + P_l = 0 \quad (2)$$

$$\sum_{i=1}^{NG} Q_{gi} + \sum_{j=1}^{NL} Q_{di} + Q_l = 0 \quad (3)$$

### 2.2. Inequality constraints

The active power generated by each unit must satisfy the maximum and minimum operating limits during contingency states

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad (4)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad (5)$$

The voltage security at each bus also consider for both cases

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (6)$$

The active power flow through each branch of the network must satisfy the security limits during both pre and post contingencies.

$$P_{ij} \leq P_{ij}^{max} \quad (7)$$

where

| | |
|---|---|
| $C_i$ | Operation cost; |
| $P_{gi}$ | Generator output; |
| $Ng$ | No. of generators; |
| $P_{di}$ | Active power demand at load bus; |
| $Q_{di}$ | Reactive power demand at load bus; |
| $P_{loss}$ | Active power loss; |
| $Q_{loss}$ | Reactive power loss; |
| $Nl$ | No. of load buses; |
| $P_{gi}^{min}$, $Q_{gi}^{min}$ | Minimum active and reactive power limits of generators; |
| $P_{gi}^{max}$, $Q_{gi}^{max}$ | Maximum active and reactive power limits of generators; |
| $P_{ij}$ | Power flow in lines between bus *i* and *j*; |
| $P_{ij}^{max}$ | Maximum limit of lines between bus *i* and *j*; |
| $V_i$ | pre contingency voltage at bus. |

## 3. PROPOSED INTERIOR POINT BASED OPF SOLUTION METHODOLOGY

In the present work, the interior point (IP) based optimization has been used as solution technique and applied to obtain the optimal generation schedules to the minimum generation cost [6]. In general, the problem defined as a non-linear optimization problem.

Minimize $f(x)$
Subject to $h(x) = 0$ (8)

and

$$g_{min} \leq g(x) \leq g_{max} \quad (9)$$

Where the objective function *f(x)* generally represents the fuel cost of generation, transmission loss, or the corrective controls, etc., *h(x)* represents the power flow equations and *g(x)* includes component and variable inequalities. In this method the inequality constraints are transformed into equality constraints by the addition of nonnegative slack variables. This modification can reformulate Equation (8) as:

Minimize $f(x)$
Subject to $h(x) = 0$

$$g(x) - z_1 - g_{min} = 0$$

$$g(x) + z_u - g_{max} = 0;\ z_1, z_u \geq 0 \quad (10)$$

where $z_1$ and $z_u$ are slack variables.
The Lagrangian function for the system of (10) may be written as

$$L = f(x) - \lambda^T h(x) - \pi_1^T (g(x) - z_1 - g_{min}) - \pi_u^T (g(x) + z_u - g_{max}) \quad (11)$$

where λ, $\pi_1$ and $\pi_u$ are the vectors of Lagrange multipliers. The KKT optimal condition for the above can be written as

$$\Delta_x L = \nabla f(x) - \nabla h(x)^T \lambda + \Delta g(x)^T \pi_1 - \nabla g(x)^T \pi_u = 0 \quad (12)$$

$$\Delta_\lambda L = -h(x) = 0 \quad (13)$$

$$\Delta \pi_1 L = -(-g(x) + z_1 + g_{min}) = 0 \quad (14)$$

$$\Delta \pi_u L = -(g(x) + z_u - g_{max}) = 0 \quad (15)$$

$$\Delta_{z1} L = Z_1 \pi_1 = 0;\ \pi_1,\ Z_1 < 0 \quad (16)$$

$$\Delta_{zu}L = Z_u\pi_u = 0;\ \pi_u,\ Z_u < 0 \tag{17}$$

Due to complimentary conditions some difficulty has to be raised in (16) and (17). These difficulties have been overcome by introducing a perturbation factor μ > 0 in Lagrangian function through the incorporation of logarithmic barrier as

$$L_\mu = f(x) - \mu\sum(\ln z_1 + \ln z_u) - \lambda^T h(x) - \pi_1^T(g(x) - z_1 - g_{min}) - \pi_u^T(g(x) + z_u - g_{max}) \tag{18}$$

when the KKT conditions are applied in (18) then (16) and (17) are transformed as

$$\Delta_{z1}L_\mu = Z_1\pi_1 - \mu e = 0 \tag{19}$$

$$\Delta_{zu}L_\mu = Z_u\pi_u - \mu e = 0 \tag{20}$$

where $e = [1, 1, 1, \dots, 1]^T$ and $\mu$ is known as the barrier parameter. The original complementary conditions are satisfied with forcing the value of $\mu$ from a non-zero value to zero value as iteration proceeds. After inclusion of the barrier parameter in (11)-(18), (19), and (20) are called the perturbed KKT conditions. By the application of Newton's method to perturbed KKT equations

$$\begin{bmatrix} \pi_1 & 0 & Z_1 & 0 & 0 & 0 \\ 0 & \pi_u & 0 & Z_u & 0 & 0 \\ -Z_1 & 0 & 0 & 0 & \nabla_{g(x)}^T & 0 \\ 0 & -Z_u & 0 & 0 & -\nabla_{g(x)}^T & 0 \\ 0 & 0 & \nabla_{g(x)} & -\nabla_{g(x)} & \nabla_x^2 L_\mu & -\nabla h(x)^T \\ 0 & 0 & 0 & 0 & -\nabla h(x) & 0 \end{bmatrix} \times \begin{bmatrix} \Delta Z_1 \\ \Delta Z_u \\ \Delta\pi_1 \\ \Delta\pi_u \\ \Delta x \\ \Delta\lambda \end{bmatrix} = -\begin{bmatrix} \nabla_{z_1}L_\mu \\ \nabla_{z_u}L_\mu \\ \nabla_{\pi_1}L_\mu \\ \nabla_{\pi_u}L_\mu \\ \nabla_x L_\mu \\ \nabla_\lambda L_\mu \end{bmatrix}$$

$$\begin{bmatrix} \pi_1 & 0 & Z_1 & 0 & 0 & 0 \\ 0 & \pi_u & 0 & Z_u & 0 & 0 \\ -Z_1 & 0 & 0 & 0 & \nabla_{g(x)}^T & 0 \\ 0 & -Z_u & 0 & 0 & -\nabla_{g(x)}^T & 0 \\ 0 & 0 & \nabla_{g(x)} & -\nabla_{g(x)} & \nabla_x^2 L_\mu & -\nabla h(x)^T \\ 0 & 0 & 0 & 0 & -\nabla h(x) & 0 \end{bmatrix} \times \begin{bmatrix} \Delta Z_1 \\ \Delta Z_u \\ \Delta\pi_1 \\ \Delta\pi_u \\ \Delta x \\ \Delta\lambda \end{bmatrix} = -\begin{bmatrix} \nabla_{z_1}L_\mu \\ \nabla_{z_u}L_\mu \\ \nabla_{\pi_1}L_\mu \\ \nabla_{\pi_u}L_\mu \\ \nabla_x L_\mu \\ \nabla_\lambda L_\mu \end{bmatrix} \tag{21}$$

where $\nabla_x^2 L_\mu = \nabla_x^2 f(x) - \nabla_x^2 h(x)^T\lambda + \nabla_x^2 g(x)^T\pi_1 - \nabla_x^2 g(x)^T\pi_1 - \nabla_x^2 g(x)^T\pi_u$

The Newton's direction has been obtained by solving (22) directly or by solving reduced system.

$$\begin{bmatrix} H & -J_h^T \\ -J_h & 0 \end{bmatrix} * \begin{bmatrix} \Delta x \\ \Delta\lambda \end{bmatrix} = -\begin{bmatrix} \psi \\ h(x) \end{bmatrix} \tag{22}$$

Firstly $\Delta x$ and $\Delta\lambda$ computing then

$$\Delta Z_1 = \nabla g(x)^T\Delta x - \nabla_{\pi_1}L_\mu$$
$$\Delta Z_u = -\nabla g(x)^T\Delta x - \nabla_{\pi_u}L_\mu$$
$$\Delta\pi_1 = Z_1^{-1}(-\pi_1\Delta Z_1 - \nabla_{z_1}L_\mu)$$
$$\Delta\pi_u = Z_u^{-1}(-\pi_u\Delta Z_u - \nabla_{z_u}L_\mu)$$

Where

$$H = \nabla_x^2 L\mu + \nabla g(x)(Z_1^{-1}\pi_1 - Z_u^{-1}\pi_u)\nabla g(x)^T$$
$$J_h = \nabla h(x)$$
$$\psi = -\nabla_x L_\mu - \nabla g(x)(Z_1^{-1}\pi_1 - Z_u^{-1}\pi_u)\nabla g(x)^T + Z_1^{-1}\nabla_{z_1}L_\mu - Z_u^{-1}\nabla_{z_u}L_\mu$$

After computing above variable updates the variables and value of $\mu$ by using new primal and dual variables.

$$x^{k+1} = x^k + \alpha_p^k\Delta x \qquad \lambda^{k+1} = \lambda^k + \alpha_d^k\Delta\lambda$$
$${z_1}^{k+1} = {z_1}^k + \alpha_p^k\Delta z_1$$
$${\pi_1}^{k+1} = {\pi_1}^k + \alpha_d^k\Delta\pi_1 \tag{23}$$
$${z_u}^{k+1} = {z_u}^k + \alpha_p^k\Delta z_u \qquad {\pi_u}^{k+1} = {\pi_u}^k + \alpha_d^k\Delta\pi_u$$

where $\alpha_p^k$ and $\alpha_d^k$ are step lengths parameters. The maximum step length has been determine by Newton's direction as following

$$\alpha_p^k = \min\left\{1, \gamma\, min\left\{-\frac{z_1^k}{\Delta z_1}/\Delta z_1 < 0, -\frac{z_u^k}{\Delta z_u}/\Delta z_u < 0\right\}\right\} \quad (24)$$

$$\alpha_d^k = \min\left\{1, \gamma\, min\left\{-\frac{\pi_1^k}{\Delta \pi_1}/\Delta \pi_1 < 0, -\frac{\pi_u^k}{\Delta \pi_u}/\Delta \pi_u < 0\right\}\right\} \quad (25)$$

To ensure that the next point will satisfy the strict positivity conditions use $\gamma$ as a safety factor. To reduced the complementary gap the value of $\mu$ should be proportional to this gap and describe as

$$\mu^{k+1} = \sigma^k \frac{\rho^k}{2p} \quad (26)$$

$$\rho^k = (Z_1^k)^T \pi_1^k + (Z_u^k)^T \pi_u^k \quad (27)$$

where $p$ is number of inequality constraints, $\rho^k$is complementary gap and $\sigma^k$ is called the centering parameter which is given by $\sigma^k = max\,\{0.99\sigma^{k-1}, 0.1\}$, with $\sigma^0 = 0.2$. The convergence of solution is terminated when these two factors becomes sufficiently small.

1. Complementary gap.
2. Norm of right hand side vector scaled by summation of all primal variables.

## 4. RESULTS AND ANALYSIS

The proposed algorithm has been simulated in MATLAB on Intel (R), Core 2 Duo and 2.66 GHz processor. In order to show the effectiveness of the proposed algorithm, modified IEEE-30 bus system with hour-ahead demand biddings have been selected. In the present system, all the generators have its own operational constrain and all of them have right to optimally reschedule the generators fulfilling objective. In this work, the IP based solution techniques are applied to obtain the optimal generation schedules to obtain the economic generation schedules. The IP based OPF algorithm has been applied with started by initialization the IP parameters. Initially, the tolerance value $\varepsilon$ is selected as $1\times10^{-4}$ and centering parameter $\sigma$ is selected in the range of (0, 1) for IP. In each trail of OPF, the convergences have been achieved within 5 to 6 iterations for modified IEEE-30 bus system respectively. It has been observed that the value of objective function is minimum using OPF for modified IEEE-30 bus system. It can be concluded that the selection of appropriate parameters provide a significant effect on the convergence of global solution.

### 4.1. Modified IEEE-30 bus test system

The standard modified IEEE-30 bus system consists of 6 generator buses and 24 load buses. In the modified IEEE-30 bus system, all generators and loads operates collectively and form a power system network as shown in Figure 1. The marginal cost functions of generators are listed in Table 1 and their connectivity in modified IEEE-30 bus system is shown in Figure 1. A typical active power load curve (24-hour) pattern on each load buses for modified IEEE-30 bus system has been shown in Figure 2. In order to observe the congestion management in the system, the transfer limits of branches are also considered in the problem formulations. The transfer limits of lines and line flows for the test system are given in Table 2 of test results.

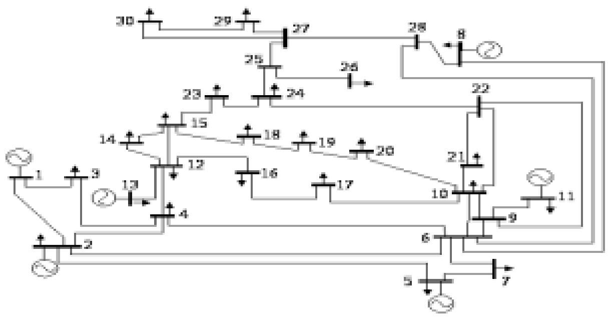


Figure 1. Modified IEEE-30 bus system model

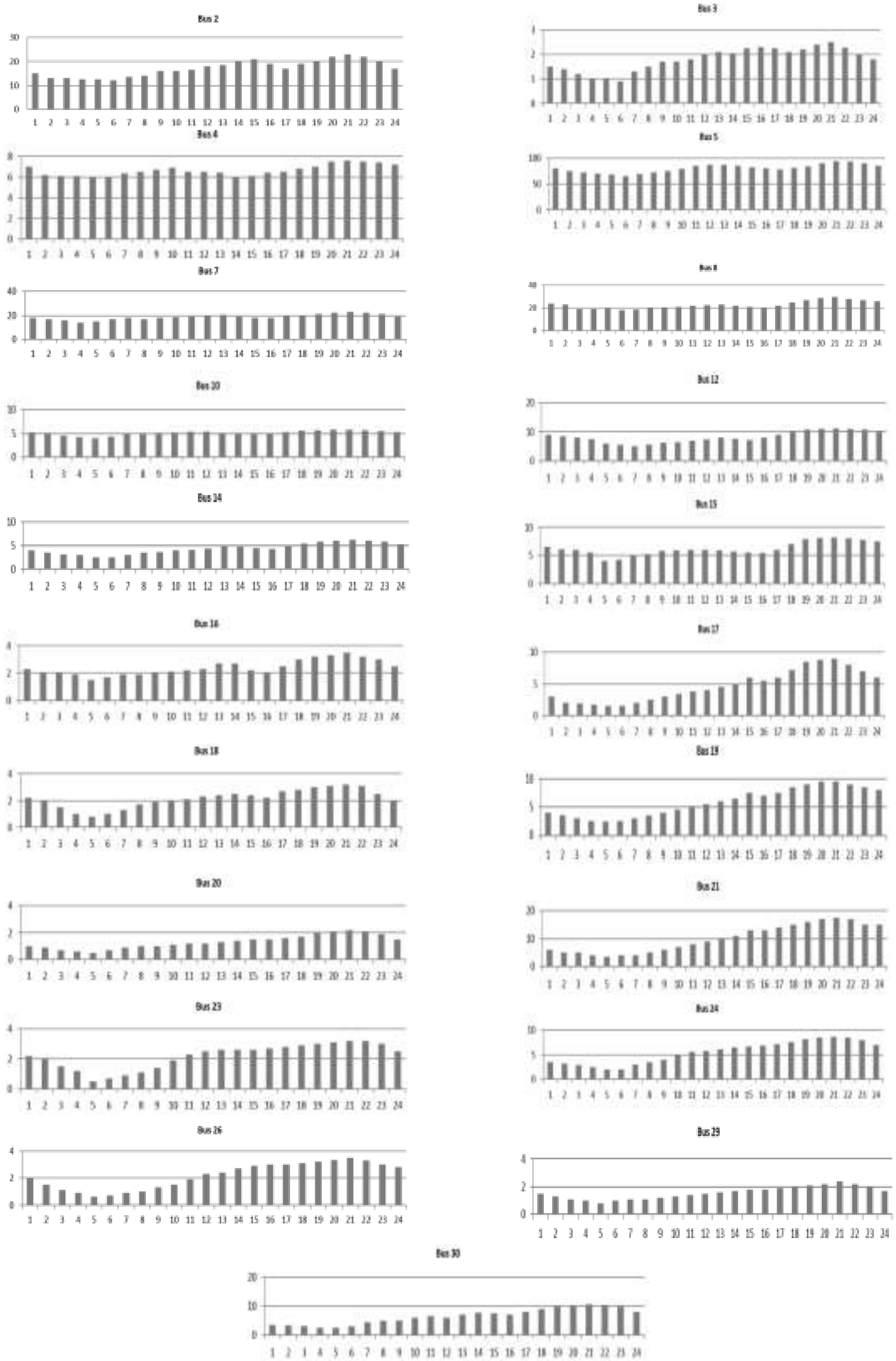


Figure 2. Load demands on various load buses in a day

Table 1. Cost Function of Generation in using Modified IEEE-30 Bus System Model

| Generator bus | $P_{max}$ (MW) | $P_{min}$ (MW) | Marginal generation cost function \$/hr |
|---|---|---|---|
| 1 | 50 | 10 | $2P+0.02P^2$ |
| 2 | 50 | 10 | $1.75P+0.0175\ P^2$ |
| 5 | 100 | 10 | $1P+0.0625\ P^2$ |
| 8 | 100 | 10 | $3.25P+0.00834\ P^2$ |
| 11 | 50 | 10 | $3P+0.025\ P^2$ |
| 13 | 50 | 10 | $3P+0.025\ P^2$ |

### 4.2. Case studies

The following cases have been considered and carried out on modified IEEE-30 bus system to find the effectiveness of OPF method using IP technique.

Case 1: Load flow analysis using initial generators schedules.

Case 2: Economic rescheduling of generators using IP based OPF method.

#### 4.2.1. Case 1: load flow analysis using initial generators schedules

In this case, initial schedules of generators and consumers demands have been considered for load flow (LF) analysis. The load variation on various load buses in a day has been shown in Figure 2 and the corresponding initial generation schedules for modified IEEE-30 bus system are shown in Figure 3.

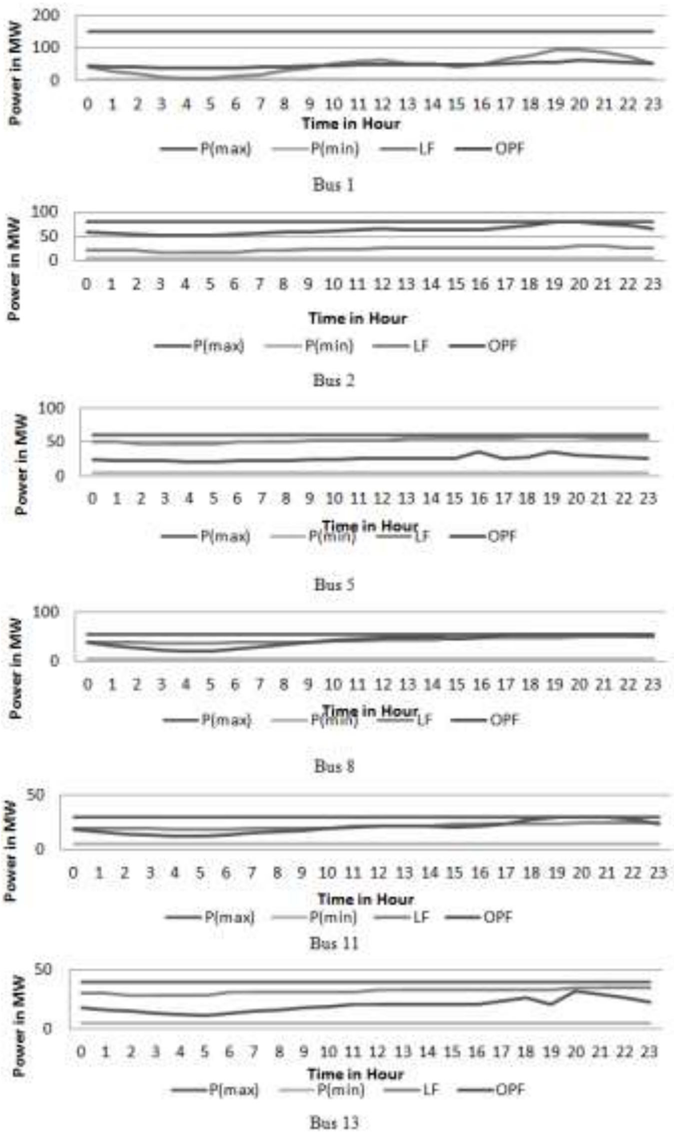


Figure 3. Active power generation schedules for modified IEEE-30 bus system using LF and IP based OPF in a day (MW)

The power flows in the lines of the system due to initial schedules have been given in Table 2. These initial schedules have been decided in such a way that the system can operates efficiently. However, the results shows that sometimes, the system technical constraints have not satisfied. Also, the results obtained by LF analysis shows that the voltage profiles of all buses have also deviated for its minimum and maximum limits. Thus, OPF based scheduling is required to fulfil the all the tec[hnical constrains.'

In the present work, the line flow limits have also considered in the problem formulation. The line flows have been given in Table 2. In Table 2, the highlighted values show the case of overflow or congestion. The results shows that after application of IP based OPF method; the lines flows comes into their respective limits and the problem of overflow or congestion have been resolved as in initial schedule. Therefore, the IP based OPF method has also provide an efficient solution for congestion management. Similarly, the voltage profile and the losses in the system have also improved with OPF based generators rescheduling.

Table 2. Power Flows in the Various Lines during Congestion (MVA)

| Congested Line No. | Transfer limits (MVA) | Solution Method | Time of congestion in the system (hours) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2am | 10am | 11am | 12am | 13pm | 14pm | 15pm | 16pm | 17pm | 18pm | 19pm | 20pm | 21pm | 22pm |
| L1 | 40 | LF | 16.25 | 40.43 | 46.96 | 44.52 | 40.62 | 41.06 | 32.32 | 35.58 | 48.13 | 56.46 | 69.14 | 97.10 | 63.48 | 54.71 |
| | | OPF | 24.58 | 29.26 | 31.80 | 30.70 | 30.64 | 32.68 | 33.39 | 31.44 | 33.08 | 34.77 | 36.43 | 38.82 | 36.21 | 33.97 |
| L2 | 26 | LF | 12.41 | 24.53 | 28.38 | 24.03 | 21.44 | 24.55 | 24.61 | 24.26 | 26.99 | 28.90 | 33.43 | 32.50 | 29.39 | 24.35 |
| | | OPF | 16.87 | 18.83 | 19.13 | 19.50 | 19.34 | 19.61 | 19.79 | 20.86 | 21.85 | 23.38 | 25.69 | 25.67 | 24.19 | 22.78 |
| L3 | 25 | LF | 16.75 | 29.93 | 34.64 | 27.48 | 24.03 | 29.20 | 31.12 | 29.16 | 29.19 | 28.09 | 30.96 | 28.46 | 25.12 | 19.52 |
| | | OPF | 13.50 | 15.01 | 15.50 | 15.08 | 14.75 | 15.24 | 15.87 | 17.02 | 17.66 | 18.94 | 21.83 | 20.33 | 19.13 | 18.03 |
| L4 | 25 | LF | 13.07 | 22.58 | 25.64 | 21.79 | 19.57 | 22.10 | 22.17 | 22.36 | 24.50 | 26.16 | 30.05 | 29.15 | 26.60 | 22.20 |
| | | OPF | 15.50 | 16.88 | 16.93 | 17.22 | 17.14 | 17.19 | 17.35 | 18.41 | 19.54 | 20.94 | 23.05 | 22.89 | 21.65 | 20.54 |
| L5 | 50 | LF | 27.06 | 70.74 | 80.11 | 63.25 | 54.03 | 61.70 | 65.33 | 57.40 | 54.48 | 50.09 | 55.98 | 54.45 | 49.81 | 42.03 |
| | | OPF | 36.31 | 45.03 | 48.03 | 44.67 | 42.83 | 41.47 | 41.24 | 40.12 | 41.59 | 43.59 | 44.07 | 48.98 | 48.13 | 46.30 |
| L6 | 30 | LF | 20.92 | 38.28 | 44.18 | 35.03 | 30.64 | 37.07 | 39.42 | 36.75 | 36.42 | 34.80 | 38.39 | 35.39 | 31.24 | 24.28 |
| | | OPF | 16.05 | 17.28 | 17.75 | 17.28 | 16.95 | 17.18 | 17.65 | 18.83 | 19.46 | 21.24 | 23.91 | 23.66 | 22.07 | 20.68 |
| L7 | 25 | LF | 24.70 | 43.04 | 48.79 | 39.21 | 34.57 | 40.82 | 42.96 | 39.72 | 38.15 | 35.76 | 39.29 | 36.74 | 32.66 | 25.75 |
| | | OPF | 14.87 | 14.93 | 14.08 | 14.93 | 14.84 | 12.99 | 12.22 | 12.51 | 12.66 | 15.58 | 14.96 | 20.83 | 18.73 | 16.87 |
| L8 | 20 | LF | 7.99 | 20.94 | 22.47 | 17.62 | 14.81 | 15.76 | 16.58 | 12.09 | 10.18 | 7.96 | 9.21 | 10.05 | 9.98 | 9.68 |
| | | OPF | 14.23 | 18.47 | 19.49 | 18.89 | 19.05 | 17.02 | 15.89 | 14.72 | 16.09 | 16.16 | 14.58 | 17.96 | 18.53 | 18.05 |
| L9 | 46 | LF | 24.29 | 47.35 | 52.09 | 43.87 | 37.43 | 38.64 | 40.59 | 35.82 | 33.18 | 30.41 | 33.45 | 35.01 | 33.85 | 31.80 |
| | | OPF | 30.16 | 41.43 | 45.39 | 40.83 | 37.31 | 36.32 | 36.41 | 34.15 | 34.39 | 35.01 | 33.59 | 39.24 | 39.24 | 38.26 |
| L11 | 10 | LF | 22.33 | 9.22 | 10.81 | 9.42 | 9.26 | 12.13 | 13.09 | 12.70 | 12.92 | 12.93 | 13.73 | 11.57 | 11.13 | 8.46 |
| | | OPF | 0.52 | 4.20 | 3.78 | 5.10 | 5.71 | 7.02 | 7.00 | 7.69 | 8.06 | 7.90 | 7.85 | 6.76 | 6.21 | 5.31 |
| L16 | 45 | LF | 42.27 | 47.83 | 52.42 | 47.73 | 45.04 | 49.91 | 52.20 | 50.73 | 50.31 | 48.24 | 50.00 | 48.05 | 45.76 | 41.59 |
| | | OPF | 15.31 | 22.72 | 41.47 | 29.06 | 26.79 | 37.43 | 44.00 | 43.38 | 43.93 | 40.33 | 43.27 | 39.81 | 34.14 | 29.67 |
| L17 | 10 | LF | 5.61 | 8.34 | 9.27 | 8.78 | 8.33 | 9.11 | 9.21 | 9.52 | 9.80 | 9.90 | 10.34 | 10.08 | 9.56 | 8.69 |
| | | OPF | 3.84 | 7.02 | 8.25 | 7.47 | 7.10 | 8.09 | 8.40 | 8.76 | 9.04 | 9.08 | 9.47 | 9.22 | 8.57 | 7.84 |
| L18 | 22 | LF | 15.17 | 21.33 | 23.55 | 21.37 | 20.73 | 23.91 | 24.11 | 24.07 | 24.70 | 24.83 | 26.00 | 24.98 | 23.74 | 21.14 |
| | | OPF | 8.55 | 16.42 | 19.76 | 16.57 | 16.23 | 19.82 | 21.05 | 16.16 | 21.91 | 21.82 | 22.70 | 21.98 | 20.21 | 18.09 |
| L19 | 12 | LF | 22.32 | 11.59 | 13.00 | 11.63 | 11.28 | 13.35 | 13.49 | 13.20 | 13.40 | 13.14 | 13.89 | 12.84 | 12.05 | 10.18 |
| | | OPF | 2.36 | 6.19 | 8.86 | 6.34 | 6.35 | 9.21 | 10.26 | 10.18 | 10.44 | 9.81 | 10.49 | 9.53 | 8.07 | 6.77 |
| L21 | 10 | LF | 20.17 | 8.47 | 9.52 | 8.05 | 7.85 | 10.18 | 10.48 | 9.75 | 9.55 | 9.27 | 9.87 | 8.69 | 8.39 | 6.87 |
| | | OPF | 0.28 | 3.22 | 5.63 | 2.90 | 3.02 | 6.28 | 7.49 | 6.99 | 6.82 | 6.09 | 6.95 | 5.45 | 4.45 | 3.48 |
| L22 | 8 | LF | 7.04 | 7.37 | 8.45 | 7.64 | 7.70 | 9.52 | 9.41 | 9.30 | 9.36 | 9.16 | 9.73 | 9.10 | 8.58 | 7.13 |
| | | OPF | 1.43 | 4.53 | 6.26 | 4.87 | 5.09 | 7.33 | 7.70 | 7.69 | 7.79 | 7.41 | 7.86 | 7.35 | 6.48 | 5.26 |
| L23 | 6 | LF | 5.94 | 4.46 | 5.10 | 4.52 | 4.58 | 6.21 | 6.25 | 5.69 | 5.81 | 5.55 | 5.98 | 5.33 | 5.05 | 4.37 |
| | | OPF | 0.16 | 1.69 | 3.02 | 1.82 | 2.07 | 4.14 | 4.67 | 4.21 | 4.34 | 3.87 | 4.31 | 3.66 | 3.01 | 2.62 |
| L41 | 10 | LF | 4.37 | 9.85 | 10.86 | 9.84 | 9.91 | 11.65 | 11.88 | 12.21 | 12.90 | 13.35 | 14.18 | 13.55 | 12.31 | 10.29 |
| | | OPF | 3.24 | 5.06 | 4.90 | 5.43 | 6.29 | 6.56 | 6.45 | 7.22 | 7.88 | 8.91 | 7.69 | 9.64 | 9.21 | 8.23 |

#### 4.2.2. Case 2: economic rescheduling of generators using IP based OPF method

In this case, all the constraints of system components and the transfer limits of the lines have been considered in the problem objective for studying problem objective and congestion management. In the present case study, suggested IP technique has been used to obtain an optimal solution for the test system using OPF. All the generators and load buses are chosen to participate in the problem objective of congestion management with minimum generation cost for the test system. The parameters selection for IP has been also been plays an important role in optimization techniques.

### 4.3. Selection of IP parameters

In the present work, the suggested IP based solution technique is applied to obtain the optimal generation schedules to alleviate the congestion in the lines. The mathematical formulation of IP method in equations (8)-(27) reveals that the performance of this method depends upon initialization parameters such as maximum number of iteration, centering parameter and tolerance value. Thus, in the initialization of IP based OPF algorithm, the maximum number of iteration $Iter_{max}$ = 50, centering parameter = $\sigma\epsilon(0,1)$ and tolerance $\varepsilon = 10^{-6}$.

After application of OPF based optimal rescheduling using IP, the generation levels are increased or decreased in modified IEEE-30 bus system to achieve the objective of the work. The rescheduled values of active power generation are shown in Figure 3 for modified IEEE-30 bus system. These figures show the variation in generation levels of generators after rescheduling with respect to initial schedules.

The generation cost and welfare (profits) obtained by generators using IP based OPF for the test system in a day has given in these Table 3. The results show that the welfare of the generators has been improved by using IP based OPF method. The total generation cost in a day for initial schedule is 18826.9 $/day and the total generation cost in a day using IP based OPF is 16475.1 $/day as given in Table 3. Thus, the result reveals that the total generation cost obtained by IP based OPF method provides substantial saving of 2351.8 $/day.

Table 3. Total Generation Cost using LF and OPF

| No. of hours | Generation Cost using Load Flow | Generation Cost using OPF |
|---|---|---|
| 0 | 697.372 | 620.13 |
| 1 | 641.445 | 558.23 |
| 2 | 599.168 | 509.65 |
| 3 | 562.515 | 472.01 |
| 4 | 541.404 | 444.59 |
| 5 | 539.382 | 441.31 |
| 6 | 590.494 | 491.27 |
| 7 | 618.602 | 527.83 |
| 8 | 654.857 | 573.65 |
| 9 | 699.268 | 616.93 |
| 10 | 769.748 | 670.75 |
| 11 | 813.561 | 705.83 |
| 12 | 838.607 | 730.23 |
| 13 | 827.254 | 728.77 |
| 14 | 829.708 | 723.81 |
| 15 | 808.758 | 702.23 |
| 16 | 831.01 | 789.3 |
| 17 | 905.447 | 801.01 |
| 18 | 984.029 | 864.2 |
| 19 | 1075.79 | 938.83 |
| 20 | 1108.94 | 977.14 |
| 21 | 1045.42 | 934.57 |
| 22 | 970.79 | 869.8 |
| 23 | 873.292 | 783 |
| Total Generation Cost in a day ($/day) | 18826.9 | 16475.1 |

These test results reveals that apart from economic generation schedule the OPF based generation rescheduling provides various other advantageous solutions for the power network operations such as congestion management and voltage control of each buses. Detailed analyses of these advantageous features have been delineated in next sub section.

## 5. CONCLUSION

In this work, load flow study and IP based OPF studies were performed on the IEEE-30 bus system and the results for both the cases were observed by comparing the results carried out by performing the LF study and OPF study. It is clear that the OPF study provides better results as compared to LF study and the results obtained by using IP based OPF does not violate the limit of the system components while the results obtained during the LF study shows that the limit of system was violated many times and the system drifted towards contingency. Also, one of the main reasons for which the study was conducted was to see the effect of OPF study on the price of the active power generation. After the comparison it is clear that use of OPF study on a system has given a significant reduction in the generation cost of the system. Hence, the present work clearly shows that the generation scheduling using IP based OPF provides better results and makes the system more efficient as well as less costly.

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