

The Effect of Congestion on Production Cost in Power System

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Abstract: - The study examines how varying maximum flow limits on critical transmission branches affect generator outputs and overall system efficiency. The findings demonstrate that enhancing transmission capacity can optimize power distribution and significantly reduce generation costs. Effective congestion management strategies, including demand response, transmission enhancements, and market-based approaches, are essential for maintaining system reliability and minimizing operational costs. This research underscores the economic and technical benefits of strategic infrastructure investments and advanced optimization techniques in power systems. This study uses a MATLAB simulation of a three-bus system to investigate the effects of varying maximum flow limitations on significant transmission branches.

Key-Words: - Congestion, Production cost, Economic dispatch, Optimal power flow, Power flow limits, MATLAB simulation.

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1 Introduction

The Economic scheduling and efficient operation are vital for the reliability and cost-effectiveness of modern power systems, [1]. Congestion and overloaded lines pose significant challenges, affecting both the stability and economic performance of power networks. Optimal Power Flow (OPF) problems, which involve nonlinear optimization, are essential for addressing these challenges by determining the optimal settings for power system control variables to achieve predefined objectives while meeting system constraints, [2]. This study examines the impact of congestion and overloaded lines on economic power system scheduling, focusing on how these issues influence generator outputs and overall system efficiency.

Power system congestion occurs when transmission networks cannot accommodate desired power flows due to capacity limitations, leading to increased operational costs and reliability issues, [3]. Overloaded lines exacerbate these problems by creating bottlenecks that hinder efficient power distribution and heighten the risk of system failures. Effective congestion management is crucial for maintaining system reliability and minimizing costs, [4]. Strategies for managing congestion include demand response, enhancing transmission capacity, and market-based approaches, [5].

This research utilizes a MATLAB simulation of a three-bus system to analyze the effects of varying maximum flow limits on key transmission branches. This simulation provides a detailed examination of how changes in transmission capacity impact power generation distribution among generators and overall generation costs, [6]. By exploring the performance of the power system under different congestion scenarios, valuable insights are gained into optimizing power distribution and reducing operational costs. Previous studies have underscored the importance of enhancing transmission line capacity for economic and efficient power system operation.

The findings of this paper contribute to a deeper understanding of the interactions between transmission constraints and economic scheduling. They highlight the potential benefits of strategic infrastructure investments in reducing congestion and optimizing power flow. This research underscores both the technical and economic aspects of managing power system congestion, suggesting that improved transmission infrastructure and effective congestion management strategies can result in significant cost savings and enhanced system reliability.

In this paper, we propose a simulated annealing (SA) algorithm to address the optimal power flow problem. The study introduces a generalized

equation aimed at determining the optimal power generation levels that minimize fuel costs, modeled using a quadratic function.

2 Problem Formulation

The objective of optimal power flow is to minimize the total cost of generation. The classic form of the formulation is

$$\min F_t = \sum_{i=1}^n F_i(P_i) = \sum_{i=1}^n (a_i + b_i P + c_i P_i^2) \quad (1)$$

The Optimal Power Flow (OPF) problem had been inherently a nonlinear optimization challenge. Its aim was to determine the optimal settings for power system control variables to achieve specific system objectives while adhering to various system constraints, [7]. The OPF problem could be mathematically expressed as follows:

$$\min F(X, U) \quad (2)$$

$$g(X, U) = 0 \quad (3)$$

$$h(X, U) \leq 0 \quad (4)$$

X and U are the vectors of dependent and control variables, respectively. $F(X, U)$ in Eq. (1) refers to the target (objective) function to be optimized. The functions $g(X, U)$ and $h(X, U)$ represent the equality and inequality system constraints, respectively, [8], [9].

2.1 Objective Function

The primary goal of solving the OPF problem had been to find the optimal combination of control and state variables that maximized or minimized a predefined objective function. The choice of the objective function reflected a thorough analysis of both the security and economic aspects of the power system. Commonly used objective functions in OPF studies included:

- Minimizing production costs.
- Minimizing active transmission losses.
- Minimizing reactive transmission losses.
- Maximizing transmissible active power.
- Minimizing the costs associated with injected reactive power.
- Minimizing the costs associated with injected active power.
- Minimizing emissions, [10].

2.2 Constraints

As mentioned before, OPF problem has both equality and inequality constraints which are to be satisfied. The constraints are segregated and provided herein.

2.3 Equality Constraints

In the OPF, power balance equations had constituted the equality constraints, represented as:

$$P_{Gi} - P_{Di} - \left| \bar{V}_i \right| \left| \sum_{j=1}^n \bar{V}_j \right| (-G_{ij} \cos(\theta_{ij}) + B_{ij} \sin(\theta_{ij})) = 0 \quad (5)$$

$$Q_{Gi} - Q_{Di} - \left| \bar{V}_i \right| \left| \sum_{j=1}^n \bar{V}_j \right| (G_{ij} \sin(\theta_{ij}) - B_{ij} \cos(\theta_{ij})) = 0 \quad (6)$$

$\theta_{ij} = \theta_i - \theta_j$, is the difference in voltage angles between bus i and bus j , n is the number of buses, P_D and Q_D are active and reactive load demands, respectively. G_{ij} is the transfer conductance and B_{ij} is the susceptance between bus i and bus j , respectively.

2.4 Inequality Constraints

The inequality constraints in the OPF reflected the operational limits of the equipment present in the power system and also the limits imposed on lines and load buses to ensure system security, [11].

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

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \quad (8)$$

$$P_{Lij} \leq P_{Lij}^{\max} \quad (9)$$

$$V_{Lp}^{\min} \leq V_{Lp} \leq V_{Lp}^{\max} \quad (10)$$

$P_{Lij}, P_{Lij}^{\max}$ are the absolute power and the maximum permissible value flowing in the branch between two buses i and j , respectively.

Q_G, P_G are the active and reactive powers injected by the generator at bus ' i '.

$V_{Lp}^{\min}, V_{Lp}^{\max}$ are the minimum and maximum voltage amplitudes at each bus, respectively.

3 Stimulated Annealing Overview

Simulated annealing (SA) is a powerful optimization technique introduced by Kirkpatrick Scott in 1983. The method draws a parallel between the process of solving an optimization problem and the cooling of molten metal, aiming to improve solid quality by finding a minimum energy state. In SA, this cooling process is mimicked to find the global or near-global optimal solution. The algorithm begins with an initial parameter T_0 (temperature), which is gradually reduced, analogous to the cooling of liquid metal until it solidifies. Each iteration generates a candidate solution. If this candidate is better than the previous one, it is accepted. However, even if it is worse, it might still be accepted based on an acceptance probability P , which is compared to a random number between 0 and 1. This probability determines whether the less optimal solution will be used to generate a new candidate in the next

iteration, [12], [13], [14]. The acceptance probability is expressed as follows:

$$P = \exp(-\Delta E / T) \quad (13)$$

where, ΔE is the change in the objective function value between the current and new solutions.

3.1 Algorithm Steps

-Initialization: Set the initial solution and initial temperature.

-Itération

- Generate a neighboring solution.
- Evaluate the change in the objective function (ΔE).
- Accept the new solution with a probability that depends on ΔE and the current temperature.
- Update the current solution and temperature.

-Termination: Stop the algorithm when a stopping criterion is met, such as a predefined number of iterations, a sufficiently low temperature, or an acceptable solution quality, [13], [14].

4 Problem Solution

This simulation of a three-bus system (Figure 1) [15] using MATLAB aims to analyze the impact of varying maximum flow limits on branches 1-2 and 1-3. The objective is to study how these changes affect generator output and overall system efficiency, providing insights for optimizing power distribution and reducing operational costs. The generator data used in the three-bus system are presented in Table 1. The branch parameters and their maximum capacities are given in Table 2.

For carrying out test, the initial temperature is fixed at 10 C°, alpha is fixed at 0.99 and max tries is 10000. The final temperature is 1e-10 C°

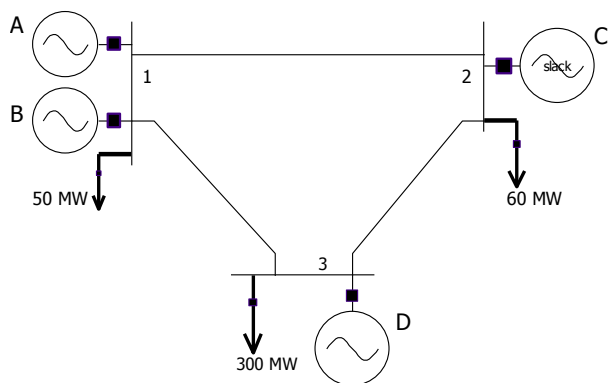


Fig. 1: Three-bus system

Source: [15]

Table 1. Generator data for the three bus-system

Generator	Capacity(MW)	Marginal cost(\$/MWh)
A	140	7.5
B	285	6
C	90	14
D	85	10

Source: [15]

Table 2. Branchdata for the three bus-system

Branch	Reactance (p.u)	Capacity (MW)
1-2	0.2	126
1-3	0.2	250
2-3	0.1	130

Source: [15]

4.1 Analyzing the Impact of Maximum Flow on Branch 1-2 in a Three-bus System

Table 3 shows the effect of increasing the maximum flow on branch 1-2 (F_{12}^{MAX}) on the power generation and the associated costs of four generators.

Table 3. Effect of the maximum flow on branch 1-2 on the operation of the three-bus system

F_{12}^{MAX}	P_A	P_B	P_C	P_D	F_{12}	Generator costs
70	0.00	239.33	90	80	69.99	3503.4
80	0.00	254.38	70.61	85	80.00	3364.9
90	0.03	275.01	62.39	72	90.00	3249.9
100	2.60	285	37.39	85	99.99	3103.0
110	20.07	285	22.51	82	110.00	2999.9
120	50.49	285	34.85	40	119.99	2973.2
130	64.00	285	11.70	49	129.99	2846.8
140	84.55	285	3.45	37	140.00	2754.2
150	109.21	285	4.13	12	150.00	2699.4
160	125	285	00	00	157.28	2647.5

Source: created by the authors

As F_{12}^{MAX} increases from 70 MW to 160 MW, the output of Generator A (P_A) increases significantly from 0 MW to 125 MW, indicating it is increasingly utilized with more transmission capacity.

Generator B (P_B) maintains a high and stable output of around 285 MW throughout, suggesting it is the most cost-effective generator.

The outputs of Generators C (P_C) and D (P_D) generally decrease, showing less reliance on these possibly less efficient or more expensive generators.

The curves in the Figure 2 provide a detailed representation of the changes in power generation for each generator.

The total generator costs decrease from 3503.4\$ to 2647.5\$ as shown in the Figure 3, indicating more efficient operation with increased line capacity, leading to lower overall generation costs. This underscores the benefit of enhancing

transmission line capacity for economic and efficient power system operation.

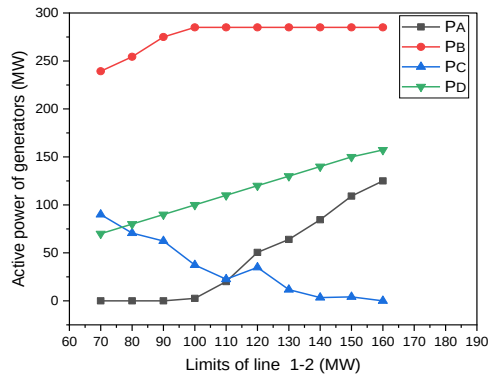


Fig. 2: Active power generation with transfer limit of line 1-2

Source: created by the authors

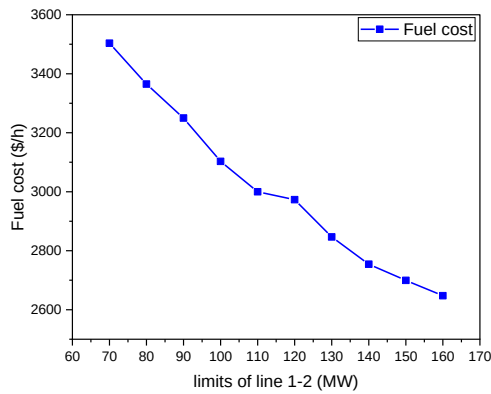


Fig. 3: Impact of line 1-2 transfer limit on fuel costs

Source: created by the authors

4.2 Analyzing the Impact of Maximum Flow on Branch 1-3in a Three-bus System

Table 4 shows that increasing the maximum flow on branch 1-3 (F_{13}^{MAX}) leads to a reduction in generator costs and a redistribution of power generated among the generators P_A , P_B , P_C , and P_D as shown in the Figure 5 , which illustrates the changes in the active power produced by each generator as the maximum capacity of line 1-3 (MW) increases.

Initially, at F_{13}^{MAX} of 100, costs are highest at 3520.3. As F_{13}^{MAX} increases, costs generally decrease, indicating improved efficiency. P_A and P_B increase their output, while P_C and P_D decrease theirs, optimizing the system's performance. The most significant cost reduction occurs between F_{13}^{MAX} of 100 and 110. This trend suggests that easing flow constraints allows for more efficient and cost-effective power generated. The active power generation corresponding to different transfer limits of line 1-3 is illustrated in Figure 4.

Table 4. Effect of the maximum flow on branch 1-3 on the operation of the three-bus system

F_{13}^{MAX}	P_A	P_B	P_C	P_D	F_{13}	Generator costs
120	00.00	243.34	81.64	85	120.00	3453.2
130	00.00	268.45	56.59	85	130.00	3252.1
140	00.00	276.01	84.67	49.31	140.00	3182.6
150	23.34	285.00	37.84	63.81	150.00	3053.0
160	38.64	285.00	42.65	43.69	160.00	3034.0
170	53.75	285.00	48.19	23.05	170.00	3018.4
180	78.21	285.00	25.22	21.55	180.00	2865.4
190	100.69	285.00	8.32	15.98	190.00	2741.6

Source: created by the authors

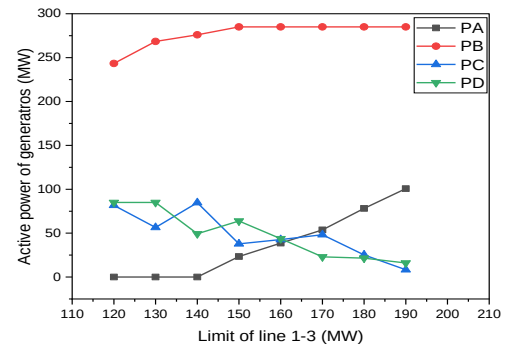


Fig. 4: Active power generation with transfer limit of line 1-3

Source: created by the authors

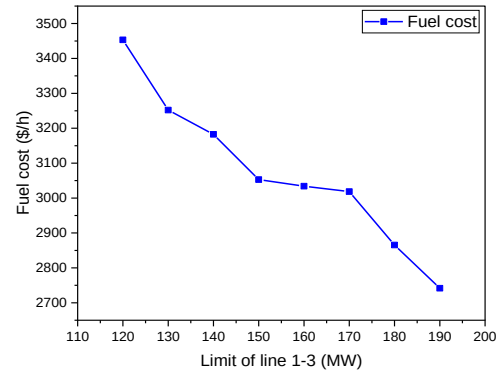


Fig. 5: Impact of Line 1-3 Transfer Limit on Fuel Costs

Source: created by the authors

5 Conclusion

This study analyzes the impact of congestion and overloaded lines on economic power system scheduling through a MATLAB simulation of a three-bus system. The results show that enhancing transmission capacity optimizes power distribution and reduces generation costs. Effective congestion management is crucial for system reliability and cost minimization, emphasizing the importance of strategic infrastructure investments and advanced

optimization techniques. The study highlights the technical and economic benefits of demand response strategies, transmission capacity enhancements, and market-based approaches. Future research should explore the integration of renewable energy sources and emerging technologies to further improve power system sustainability and resilience.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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