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Minimization of Transmission Congestion Cost using P-OPF based LSF, PSO, and ANN Techniques

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ABSTRACT- The inclusion of renewable energy sources (RES) into a stabilized network has opened gates to numerous optimization problems. Optimization of RES generation might not imply merely the myth of high availability, but it is furthermore fenced by parameters such as transmission line power flow patterns, having the optimized location, bus nodal pricing (LMP), congestion scenario, congestion cost and reliability margins of the system (ATC, TRM). Integration of RES also drags towards the congestion episode within the transmission system. The uncertain behavior of renewable energy initiates uncertainty into the system from generation perspective. These uncertainties lead to congestion which alters the linear sensitivity factors (LSF), LMP and reliability margins of the network. The congestion scenario may jeopardize the security of transmission network hampering the limits of transmission lines. The change in marginal values reflects the occurrence of congestion with additional congestion cost. Different optimization tools have been introduced in order to optimize various objectives like optimization of generation, rescheduling generators, load curtailment *etc*. In this work we have presented optimization of congestion cost (*i.e.* Congestion Management in terms of economics) post inclusion of uncertain RES (here wind and solar source are considered) into the system. The optimization problem is resolved using Probability Optimal Power Flow (P-OPF) based Particle Swarm Optimization (PSO) technique in MATLAB-MATPOWER software with Area Based Congestion Management (ABCM).

Keywords: Available Transfer Capability, Transmission Reliability Margin, Congestion management.

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1. INTRODUCTION

A transmission network is considered to be in a congested state when the generation and utilization of energy push the system to operate at or beyond its transmission limits, including thermal, stability, and voltage constraints. Such congestion compromises both the physical security and economic efficiency of the power system. Various factors contribute to transmission congestion, including transmission line overloading, generator and transmission line outages, high load demands, inadequate reactive power support, and the stochastic nature of renewable energy sources (RES). The integration of RES, such as wind and solar energy, into an already stable grid introduces uncertainties due to their inherent variability and unpredictability. These uncertainties stem from changes in network configuration, system outages, and forecast inaccuracies of RES generation. Transmission congestion results in several challenges, such as market irregularities, suboptimal market performance, RES curtailment (reducing generation to eliminate congestion), and an increase in generation costs. The presence of congestion also affects congestion costs, leading to inefficiencies in market operations. Effective congestion management is crucial to balance physical constraints with market efficiency and ensuring overall system reliability. Since constructing new transmission lines is often constrained by social and environmental factors, utilities must focus on optimizing the use of existing transmission infrastructure through power flow monitoring and control. The integration of RES alters power flow patterns, potentially leading to congestion and affecting key sensitivity factors of the system, such as Generation Shift Distribution Factors (GSDF), Power Transfer Distribution Factors (PTDF), and Line Outage Distribution Factors (LODF) [1]. Variations in these factors influence changes in the reliability margins of transmission lines, such as Available Transfer Capability (ATC) and Transmission Reliability Margin (TRM) [2]. As a result, disparities in Locational Marginal Pricing (LMP) arise, reflecting congestion costs and market inefficiencies. Several congestion management techniques have been explored, including deterministic methods such as Probabilistic Energy Management (PEM) and Monte Carlo Simulation (MCS), sensitivity factor-based approaches, auction-based congestion management, pricing-based strategies, and generator re-dispatch methods. Additionally, biologically inspired algorithms, such as Genetic Algorithms (GA), Artificial Neural Networks (ANN), and Circulatory System-Based Optimization, have been utilized for congestion management. Cluster-based

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congestion management focusing on optimal reactive power rescheduling has also been proposed as an effective strategy [3]. Different algorithms are developed and run to understand the impact and behavior of congestion on the market concentrations [4]. Integrating sporadic RES generation into a stabilized power system possibly will entail additional cost (here congestion cost) to system owing to wind intermittency increasing system instability [5]. Multi objective optimization tools such as PSO, GA overcomes the bottlenecks of traditional methods (PEM, Monte Carlo simulation, weight constrained OPF, *etc.*) like computational burden, efficiency, consideration of constraint variables, *etc.* [6, 7, 8]. Transmission Congestion Management is related to the calculating the transmission system parameters so that transmission limits are analyzed [9].

This paper analyzes transmission system power flow patterns under the influence of uncertain renewable energy sources, specifically wind and solar power. Various scenarios are simulated, and a congestion management technique using Particle Swarm Optimization (PSO) with Preventive Optimal Power Flow (P-OPF) is applied to determine the optimal location of renewable generation within the grid. The objective of this optimization is to minimize congestion and associated costs while considering multiple power system conditions over a series of 1000 test runs. Proper placement and sizing of RES within the grid can mitigate congestion by redistributing generation dispatch effectively. This study extends previous work by presenting Area-Based Congestion Management (ACM) with RES integration as a nonlinear problem solved using PSO. The research is structured as follows: first, the uncertainties in RES data (wind and solar) are examined using a test case. Next, the optimization methodology and algorithm are discussed. Finally, an analysis is conducted to explore the relationship between transmission congestion and congestion economics, considering factors such as RES availability, location, and size, as well as sensitivity factors and reliability margins. The IEEE 30-bus test system is used to evaluate transmission congestion economics under the proposed methodology. This study employs a modified IEEE 30-bus system integrated with RES to simulate power flow scenarios, comparing congestion management methodology. Additionally, real-time data for wind and solar sources are analyzed. The paper is organized into sections, beginning with data analysis and test case discussions. Problem formulation is then divided into two parts, leading into the solution methodology. Finally, results are presented, followed by discussion, conclusions, and future research directions.

2. DATA ANALYSIS and TEST CASE SYSTEM

2.1. Data analysis

The real time data received from IMD, Pune is analyzed and presented in previous analysis [5]. The PDF distribution and random 1000 generation sample of each wind and solar data are obtained in Math-wave and MATLAB software. The wind speed data has lognormal distribution, whereas the solar insolation is found to be normally distributed. The detailed power output conversion of stochastic wind speed and solar insolation is presented in [7, 8]. From the analysis it is observed that June month for wind speed and May month for solar insolation are found to be highly uncertain and most unpleasant month based on the variance calculated. Only highly uncertain months for both the RES are considered for further analysis to have worst case zone, while variation of remaining months is found to be below the highly variant month. A suitable practical model of wind-turbine generator set and solar insolation kit is considered to compare the power outputs of each. A wind farm with 13 wind turbine generator sets and a solar farm consist of 2 generator sets inculcating of 20MW inclusion of RES into the system. Later on, for the analysis of congestion management, the uncertain RES generation of 20MW is integrated at different areas.

2.2. Test Case Modification

The power flow is carried on IEEE 30 bus test system consisting of 6 generators, 30 buses and 41 transmission lines [8] which is modified into 4 areas based on geographical parameter for ACM. All the 4 areas are interconnected *via* 9 tie lines for power exchange within the area. The bus and line data of the transmission system and its single line diagram is as given in [8]. The *figure 1* represents the modified area-based block diagram of IEEE 30 bus system with tie lines and their limits.

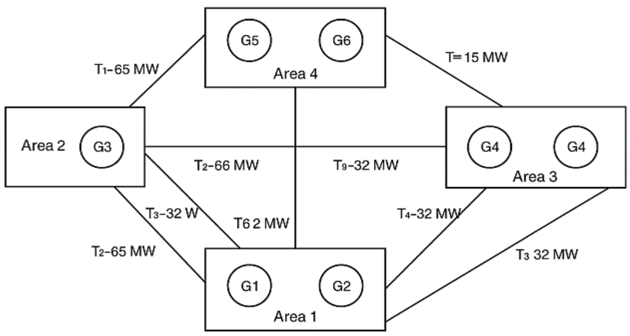

Figure 1. Area block diagram of IEEE 30 bus system with tie lines

Table 1. Tie lines details

Tie line	Interconnecting buses	Interconnecting areas	Line number	Line limit (MW)
T1	4-12	1-2	15	65
T2	10-17	1-2	26	32
T3	10-20	1-3	25	32
T4	10-21	1-3	27	32
T5	10-22	1-3	28	32
T6	15-18	2-3	22	16
T7	15-23	2-4	30	16
T8	22-24	3-4	31	16
T9	8-28	1-4	40	32

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Table 2. Generation details

Generator	Bus number	Area	Capacity (MW)
G1	1	1	23.54
G2	2	1	60.97
G3	13	2	37.00
G4	22	3	21.59
G5	23	4	19.2
G6	27	4	26.91

Each area is collection of buses and represented as a single bus; all the 4 areas are interconnected to each other for power transaction. The power flows of these interconnected lines are observed during the analysis. Only generation and tie line details are presented here. The *table 1* and *2* shows the tie line and generation details of the system respectively. Inter area transactions are performed including (N-1) contingency and inclusion of RES is done into the system which is discussed in brief later. Here the line with highest values of GSDF and PTDF is constrained to calculate LODF.

3. PROBLEM FORMULATION

The methodology adopted is based on optimal power flow of the system considering linear sensitivity factors (GSDF, PTDF and LODF), reliability margins (TRM) and LMP of the system. DC-P-OPF is run to obtain the power flow of the lines as base case in presence of conventional generators only. Later on, uncertain RES is included into the system which adversely affects the power flow into the transmission lines. Again DC-P-OPF is run to obtain the new power flow through the lines. Based on the differences obtained in the power flow linear sensitive factors (GSDF, PTDF) are calculated for each line. Later on, (N-1) contingency is created by line outage and LODF is calculated. The detailed mathematical calculation of these factors is discussed in [5]. The algorithm to obtain TRM and LMP of the system is presented in [8]. In this analysis, results of previously done work [5, 6, 7, &8] are carried on. *Table 3, 4* and *5* represents different locations of RES generation within the network, Import and export of power between the areas and overall export (-) and import (+). Area 4 is considered as sink area for reference point.

Table 3. Details of location of RES cases

Case Number	Base Case	Case 1	Case 2	Case 3	Case 4	Case 5
Case Description	No RES	RES Area1	RES Area2	RES Area3	RES Area2	RES Area3
Location of RES Generation	-	Bus 2	Bus 13	Bus 22	Bus 23	Bus 27

Table 4. Import and export between area

CASE	Area A1-A2(MW)		Area A3-A4(MW)	
	Generation (MW)	Load (MW)	Generation (MW)	Load (MW)
Base	84.51	104.5	56.2	45.1
WF-A1	84.51+(20 RES)	104.5	56.2	45.1
WF-A2	84.51	104.5	56.2+20 RES	45.1
WF-A3	84.51	104.5	56.2	45.1
SF-A1	84.51+(20 RES)	104.5	56.2	45.1
SF-A2	84.51	104.5	56.2+20 RES	45.1
SF-A3	84.51	104.5	56.2	45.1

Table 5. Import and export between area 3 and overall area wise import export for each case

CASE	Area A3(MW)		Import(-)/Export(+) (MW)		
	Generation (MW)	Load (MW)	A1	A2	A3
Base	48.5	39.6	-20	11.1	8.9
WF-A1	48.5	39.6	00	00	00
WF-A2	48.5	39.6	-20	20	00
WF-A3	48.5+(20 RES)	39.6	-20	00	20
SF-A1	48.5	39.6	00	00	00
SF-A2	48.5	39.6	-20	20	00
SF-A3	48.5+(20 RES)	39.6	-20	00	20

The objective function of P-OPF is maximization of active power generation. The problem is formed as:

Objective function: Maximize active power generation
Subject to :{ Active power balance equations;
Transmission line flow limits;
Bus voltage limits;
Active generation limits;
RES generation uncertainty}

Power transactions are made between the areas to understand tie line flows, linear sensitivity factors and reliability margins for different location of variable RES power output.

4. SOLUTION METHODOLOGY

Power system simulation package of MATLAB- MATPOWER is used for the DC-Probabilistic Optimal Power Flow (DC-P-OPF) simulation. To attain the optimality of the objective, function the 3 methodologies LSF, PSO and ANN are chosen. For LSF methodology, three factors calculated are Generation Shift Distribution Factor (GSDF) reflecting the generation perspective of the power system, Power Transfer Distribution Factor (PTDF) representing the transmission perspective of the grid and Line Outage Distribution Factor (LODF) for end user and contingency scenario.

All the factors GSDF, PTDF and LODF combined together represents the overall power system scenario. The congestion management using PSO methodology approaches by the re-dispatch of active power by selection of most sensitive generators to participate in the congestion management post inclusion of RES farm at different locations. The line limits, power flow, and wind farm output are used as the constraints which acts as limits of the search space for the particles to find the optimized location of RES farm (particle) to relieve the congestion in the transmission lines based on their power flow, with minimization of congestion cost (fitness function). The parametric values of PSO are given below:
Population size (NP) = 50;
Maximum number of functional evaluations = 5000;
Maximum number of generations = 30;
Acceleration constants (C1andC2) = 2.0;
p = particle (different location of RES generation into the areas);
g = fitness function (congestion cost).

Here, p_{best} is the optimized location of RES source (representing particle) and g_{best} is the minimized congestion cost. For p_{best} we have obtained g_{best} value to relieve congestion within the system based on transmission power flow. The output is obtained in terms of p_{best}(optimized location) and g_{best} minimized LMP (congestion cost) values for each case as discussed in *table 3, 4* and *5*. ANN has superior application in economic dispatch, load forecasting, managing congestion, and fault diagnosis and security assessment in a power system. Managing and reliving congestion using ANN methodology here implements Back Propagation Algorithm (BPA) with a 10 hidden layer network. The inputs used here were the RES uncertain output (real time as per the distribution function of both wind and solar source), transmission line limits (voltage, stability and thermal), line outage (for N-1 contingency) and load demand (real time as continuous function). The minimized congestion cost and relieved congestion from transmission lines serves as output for the methodology. The next section presents the results obtained in terms of minimized congestion cost, congestion management with optimized location of RES generation with help of tables and graphs.

5. RESULTS

All the 3 methodologies were run with set parametric values on IEEE standard 30 bus system integrated with RES source. Results were recorded for each case as discussed above for each methodology. Firstly, the methods are compared for power flow in transmission lines detecting the congestion within the lines compared with conventional generation power flow (no congestion case) and secondly, comparison is done for estimation of congestion cost with base case (no congestion cost). For reflective review and analysis of all the methods used, we have considered error parameter for comparison of their performance in reference with their actual values. *Figure 2* represents the congestion scenario based on power flow of transmission lines for all 3 methods and conventional generation case, whereas *table 6* statistically compares performance of the 3 methods.

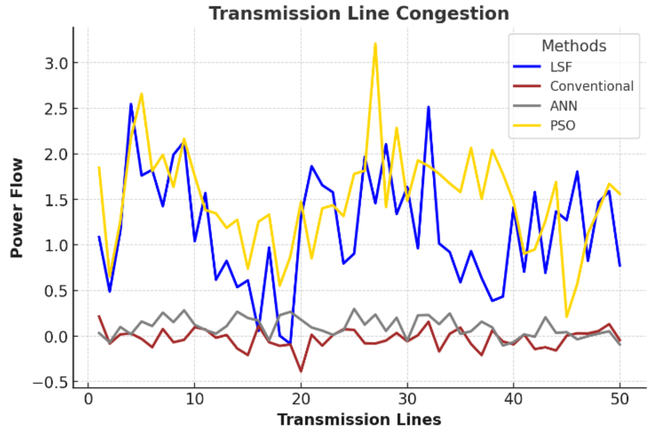

Figure 2. Transmission line Vs Power flow for Conventional, LSF, PSO and ANN methodologies representing congestion scenario

Table 6. Statistical parameters for comparison of 3 methods for power flow compared to base power flow

Method used	Absolute error ϵ	Mean error µ	Standard deviation σ	Correlation
LSF	49.19	20.99	98.64	-0.93060
PSO	150.55	48.35	290.25	-0.3103
ANN	7.55	11.47	39.08	0.36417

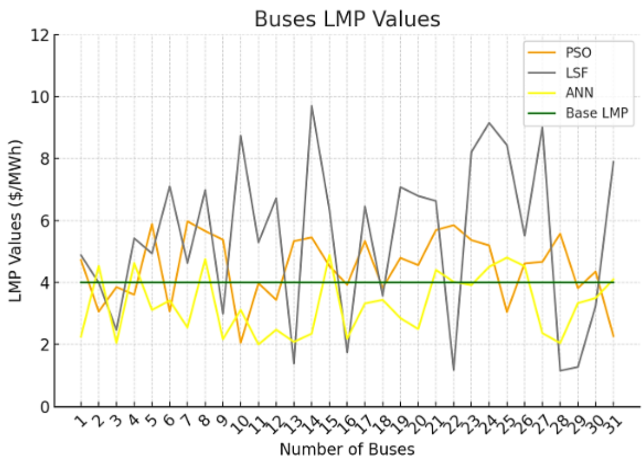

Figure 3. Bus LMP values for Conventional, LSF, PSO and ANN methodologies representing congestion cost estimation

Figure 3 represents the bus LMP values representing the congestion cost inclusion in the electricity price due to presence of congestion in the transmission lines for all 3 methods and conventional generation case as reference base case representing no congestion scenario with no congestion cost inclusion in the electricity pricing, while *table 6* statistically compares performance of the 3 methods for estimation of buses LMP values. *Table 7* shows RES curtailment percentage by all the 3 methods to manage the congestion and mitigate the

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congestion cost. The nest section discusses the results obtained for all the methodologies.

Table 7. Congestion Management by RES curtailment using LSF, PSO and ANN

Parameter	LSF			PSO			ANN		
	A1	A2	A3	A1	A2	A3	A1	A2	A3
Average area LMP($/MWh)	920.4	782.4	882.5	698.5	666.1	656.8	685.2	656.2	685.2
Maximum actual power output(MW)	104.51	76.2	68.5	104.51	76.2	68.5	104.51	76.2	68.5
Curtailed power (MW)	6.9	7.1	9.5	12.7	8.8	9.5	3.8	5.2	4.2
% Curtailment	6.60	9.31	13.8	12.5	11.54	13.8	3.6	6.8	6.1

6. DISCUSSION and ANALYSIS

In results, *figure 2* shows the power flow variation obtained by all the 3 methods compared to conventional generation power flow. All the 3 methods reflected vague difference in power flow representing prescence of congestion in transmission lines post RES integration in different areas. It can be clearly understood from *figure 2* and *table 7*, wrt power flow, LSF methodology shows higher congestion as compared to PSO and ANN varied from conventional power flow.

ANN shows less erros as compared to remaining two methods while depecting less variation in power flow, while PSO fails to present accurate congestion scenario as the variation in power flow remains constant for most of the lines. *Table 6* shows the error of all 3 methods with co relation factor symbolising the congestion power flow with actual power flow in the transmission lines. For exact estimation of congestion within power lines, LSF proves to be a better method as compared to ANN and PSO. *Figure 3* and *table 7* represents inclusion of congestion cost into electricity prices due to prescence of congestion within the power lines. estimation of LMP values can be seen very high for LSF methodology followed by PSO and least LMP values are observed for ANN method. But in contrast there are huge spikes seen in LMP values for PSO method at certain busses. ANN method estimates lesser LMP values near to base LMP values. PSO has the least correlation factor and higher absolute error, standard deviation.

7. CONCLUSION AND FUTURE SCOPE

Figures 2 and *3* present a comprehensive analysis of congestion detection and the associated costs within the system, comparing them to the conventional scenario that assumes no congestion. As outlined, the Linear Sensitivity Factor (LSF) method stands out for its ability to capture the full spectrum of power system behavior, making it particularly adept at reflecting line congestion. In contrast, methods like Particle Swarm Optimization (PSO) and Artificial Neural Networks (ANN) are reliant on large volumes of historical data, including RES (Renewable Energy Sources) power output, filtration, and fitting of data points. This reliance can hinder PSO's ability to determine the accurate power flow patterns under current system conditions.

The Locational Marginal Price (LMP) of buses is influenced by several factors, such as the location of RES generation, the output from these sources, and the flow of power across the network. In this regard, ANN proves to be more efficient than both the PSO and LSF methods. While LSF, being deterministic, tends to predict higher LMP values, it may not accurately capture real-time power flow dynamics as effectively as ANN. Despite its statistical superiority over PSO, LSF's lack of self-learning capabilities limits its ability to adapt to changing system conditions, making it less effective when compared to ANN. Thus, LSF is best suited for power system planning stages, where it provides reliable predictions based on fixed parameters. On the other hand, PSO and ANN methods are more applicable during operational periods of the power system. These methods, although data-intensive, offer greater flexibility in optimizing performance, managing congestion, and minimizing associated costs while ensuring maximum utilization of RES power with minimal curtailment.

This analysis can be further expanded to include a wider range of RES technologies and more diverse electrical network configurations. The ANN methodology, in particular, holds promise for pattern recognition and the proactive identification of potential congestion, offering valuable insights for future operational and planning decisions.

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