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Comparative Analysis of Congestion Management Methods with Integrated Renewable Energy Generation

Poonam B. Dhabai[1], Neeraj Tiwari[2], Sunil Kumar Gupta[3]
[1]*Research Scholar, Department of EE, Poornima University, Jaipur, India; dhabaipoonam@gmail.com*
[2]*Professor, Department of EE, Poornima University, Jaipur, India; neerajtiwari.1407@gmail.com*
[3]*Professor, Department of EE, Poornima University, Jaipur, India; sunil.gupta@poornima.edu.in*

***Correspondence:** Poonam B. Dhabai; *dhabaipoonam@gmail.com*

ABSTRACT- Inclusion of renewable energy in power grid at micro and macro level has imposed numerous challenges in the recent years. Occurrence and managing congestion in the power transmission line due to unpredictable and stochastic nature of Renewable Energy Source (RES) integration has become a challenging task to the grid operators. Transmission lines operate at bottlenecks during a congestion episode adding to the extra congestion cost and risk in grid stability which becomes burden to the generation as well as end users. Different methodologies are applied to detect and manage the congestion to eliminate the congestion cost factor and maintain grid stability. The presented analysis compares conventional methodology Linear Sensitivity Factors (LSF) and Heuristic methodology Particle Swarm Optimization (PSO) and Artificial Neural Network (ANN) methods for congestion management in power transmission lines with integrated RES (wind and solar) system. For comparative analysis, a modified standard IEEE 30 Bus system is chosen which is integrated with real time RES generation. Optimal locations of RES generation with minimized congestion cost and percentage of RES curtailment are chosen as objective function for comparison of the methodologies.

General Terms: Renewable energy, Integration, Congestion cost.
Keywords: Linear Sensitivity Factors, Particle Swarm Optimization, Artificial Neural Network, Congestion management.

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1. INTRODUCTION

Integration of RES in deregulated system have been a booster for supplying the exponential increase in power demand with striking advantage of being freely available to use. Despite its free availability, integration of stochastic RES into a stabilized grid has imposed many challenges like breach of transmission line limits, market instability, and congestion episode making lines to operate at bottlenecks imposing an extra congestion cost. Managing the congestion becomes a challenging task for the system operators to maintain grid and market stability. Presence of congestion in the system introduces congestion cost factor in the pricing system fluctuating the market balance. The congestion cost compensation is still a debate for both generation as well as end users of the system. The available congestion management methodologies aim at an optimal solution between managing congestion and nullifying or minimizing the congestion cost factor. Different methodologies are adopted by grid operators to prefer optimality of minimizing congestion and congestion cost while maintaining grid stability and using the available RES power at given moment. Conventional methods like Monte-Carlo, point estimation method, bootstrap method, LSF are chosen due to their accuracy whereas methods like PSO, ANN have less computational time required to achieve the optimality solution. Congestion management (CM) techniques can be applied at generation end, transmission end as well as at end users. The generation end congestion management techniques imply of optimal location of the generation, generation curtailment and generation rescheduling, whereas the transmission end congestion management techniques concentrate on optimal power flow strategies, optimal placement of FACTS devices, and reliability parameters based. The end user congestion management method focuses on demand response management, nodal pricing, zonal pricing, load curtailment, market splitting and auction-based schemes. For RES integrated grids, curtailment of RES generation irrespective of its availability has become a favorable option for the system operators to manage the congestion in the system. Curtailment of RES has now become a serious backlash from RES power generation point of view affecting the revenue of RES plants. The paper is organized in different sections starting with deep literature survey followed by data analysis and test case system, later problem formulation is presented in two sub parts followed by the solution methodology. At last results are presented with discussion and analysis. Conclusion and future scope to the problem stated is shown.

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2. LITERATURE REVIEW

Chein.Ning.et.al introduced an easy methodical method for transmission CM by recognizing groups of system users having alike effects [8]. A. Vergnol.et.al proposed two types of market-based strategies that solved the congestion prediction and maintaining system state trouble in case of limited congestion what time included with the renewable energy [24]. K. Neuhoff.et.al. modeled the present methods for domineering congestion at worldwide limits and compared the results beneath altering diffusion of wind plant with a model that replicated an included European network utilizing locational marginal pricing (LMP) [23]. The point of authors was to enumerate whether on the road to recovery system intend can create improved use of network capacities. Authors analyzed a European power market dataset and used three models for the computation: ECOFYS form to compute nodal price, MADRID & DREDSEN models to compute dissimilarity among zone cost and nodal cost ensuing from NTC calculations.

S.Z. Moussavi.et.al. proposed a new squat term forecasting algorithm for congestion, LMPs, and one-time power system variables based on notion of organization patterns-amalgamation of rank flags for generation unit and transmission lines [19]. The algorithm ended use of two partisan techniques to trim down the quantity of necessary data. S.K. Soonee.et.al. tinted the growth of RES market and the challenges faced ahead. The authors under took 4 stages of RES process: accreditation, registration, issuance & redemption. It was observed that amongst total registered projects among RES mechanism, RES generators based on wind energy contributed most about 57% while, the issuance of RECs registered a normal monthly expansion rate of 96%.

Farazameh.Haghigat.et.al. analyzed the impact of RES consumption on the economics of India [9]. The authors also defined concepts like grant/subsidy, acceleration, depreciation, tax concession/exemption, renewable purchase obligation, preferential tariff. Debre. Lew. et.al. examined experiences with curtailment on bulk power system internationally discussing how much curtailment are occurring, why is it occurring, mitigation of curtailment [8]. The authors noted down the reasons for curtailment of RES as transmission congestion, minimum operating level of conventional plants, back feeding at distribution level and stability issues. In this analysis, we have compared LSF, PSO and ANN techniques to have optimal congestion management with inclusion of RES into the grid. In this presented analysis, a modified standard IEEE 30 bus system integrated with RES generation is considered. Power flow is run for different scenarios discussed in later sections to compare the results of different methodologies. The paper also discusses the data analysis for real time data of wind and solar sources.

3. DATA ANALYSIS AND TEST CASE SYSTEM

The IEEE 30 bus system considered for the analysis is integrated with wind and solar sources, real time data is collected for a period of a year for Pune, India region. This data is statistically analyzed and power output is calculated for uncertain RES input.

3.1 Wind data analysis

The wind speed data was available in kilo-meter per hour and then converted to meter per second (mps) system for convenience. Each day is divided into 8 slots. Each slot consists of 3 hours. 56 observations per week are obtained. The recorded data was arranged month wise on hourly basis. The distribution of the data was analyzed using Easy-Fit-5.6 software tool. It was observed that the gust wind speed data followed Weibull distribution based on Chi-square goodness of fit test.

The scale parameter α value for the given wind speed data distribution is observed to be 3.1129 m/s, controlling the abscissa scale of the wind speed data distribution whereas; the shape parameter of the Weibull distribution β value is 1.364, determining the width of the data distribution. *Figure 1* and *2* shows PDF curve of wind speed and wind power output curve respectively with respect to different wind speeds.

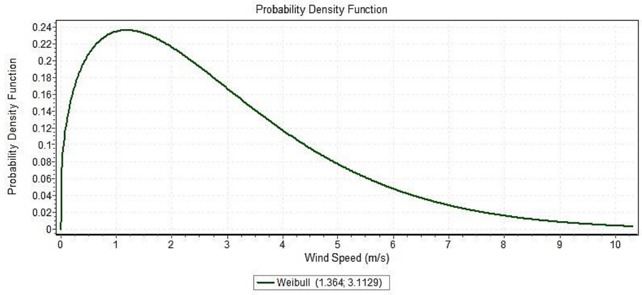

Figure 1. Weibull unbounded distribution of wind speed data

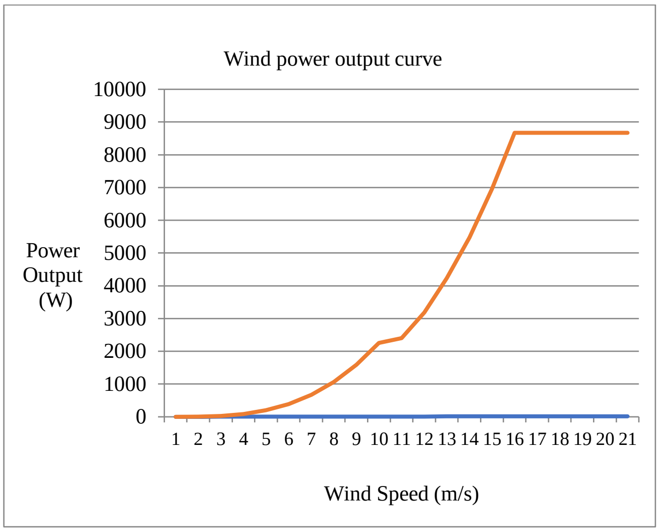

Figure 2. Wind power output curve for gust wind speeds

3.2 Solar data analysis

The real time data is obtained from morning 5 hours to evening 18 hours at interval of one hour for complete year. The solar insolation data was available in MJ/m^2; it was converted in W/m^2. The distribution of the solar insolation data followed normal distribution based on Chi-square goodness of fit test. *Figure 3* and *4* shows PDF curve of solar insolation and solar

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power output curve respectively with respect to different solar insolation level.

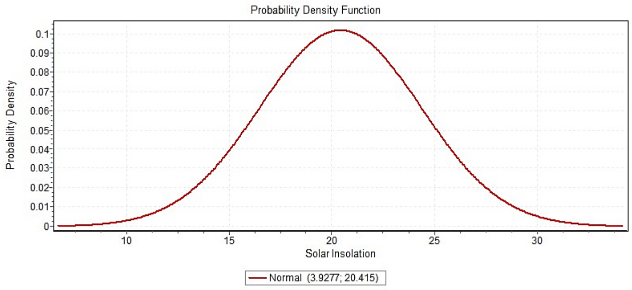

Figure 3. Normal distribution of solar insolation data

Later on, the RES farms are modeled to power output of 20MW. To include the uncertainties in the solar power output, based on the variance, 1000 random samples of RES power output distributed normally around the mean value were generated in MATLAB environment.

3.3 Test case

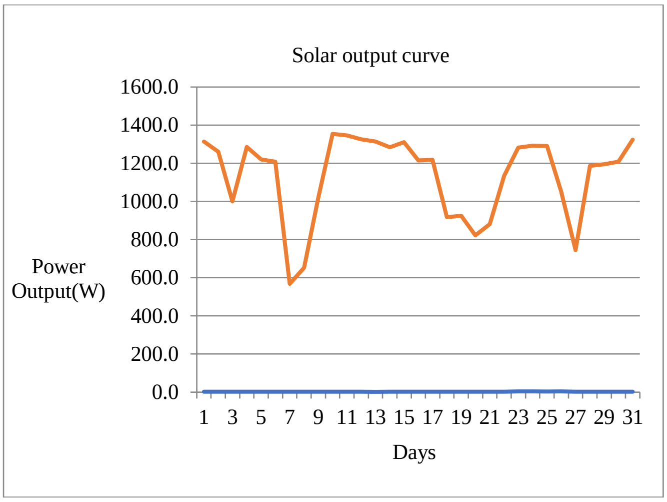

Figure 4. Solar power output curve for daily total solar insolation level

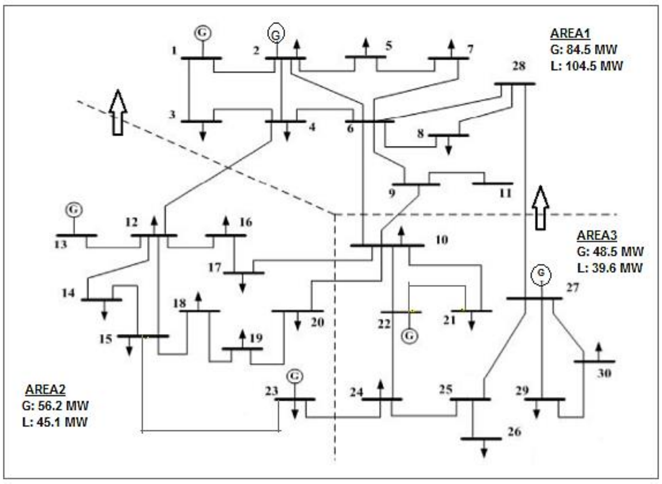

Figure 5. Single line diagram of Standard IEEE 30 Bus System divided in 3 Areas

The 30-test bus system here consists of 6 generators, 21 loads, 30 buses and 41 interconnecting transmission lines. The transmission system is modified and divided in 3 different areas based on geographical parameter represented as Area 1, 2 and 3. All the 3 areas are interconnected via 7 tie lines for power exchange within the area. *Figure 5* shows the modified IEEE 30 bus test system in 3 areas.

The tie lines with line flow limits, generation capacity and 3 area details of the 30-bus test system are shown in table 1, 2 and 3 respectively. To analyze the location impact of RES, 5 different location cases within the 3 areas with a base case are considered. The case details are discussed in *table 4.*

4. PROBLEM FORMULATION

In order to compare the chosen 3 methodologies, the mitigation of curtailment of RES and congestion management is divided and analyzed in two sub problems. Sub problem 1 of the problem analyzes the uncertainty impact on the power flow patterns of the transmission lines; whereas sub problem 2 describes the location impact of RES farm on the congestion and curtailment management.

Area import and export details for conventional generation as well as wind farm (WF) and solar farm (SF) is as shown in *table 5 and 6.*

Table 1. Interconnecting tie lines details

Tie line	Interconnecting buses	Interconnecting areas	Line number	Line limit (MW)
T1	4-12	1-2	15	65
T2	6-10	1-3	12	32
T3	9-10	1-3	14	32
T4	10-17	1-2	26	32
T5	10-20	1-2	25	32
T6	23-24	2-3	32	16
T7	27-28	3-1	36	16

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	2	19.2
G6	27	3	26.91

Table 3. Area details

Parameter/ Area	Area 1	Area 2	Area 3
Buses	1,2,3,4,5,6,7,8,9 ,11and 28	12,13,14,15,16,17,1 8,19,20 and 23	10,21,22,24,25, 26,27, 29 and 30
Generator on Bus	1,2	13,23	22,27
Total generation	84.5 MW	56.2 MW	48.5 MW
Total load	104.5 MW	45.1 MW	39.6 MW

Table 4. 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 5. Import and export between area 1 and 2

CASE	Area A1(MW)		Area A2(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 6. 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}

5. 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 4. 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.

6. 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 6 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.

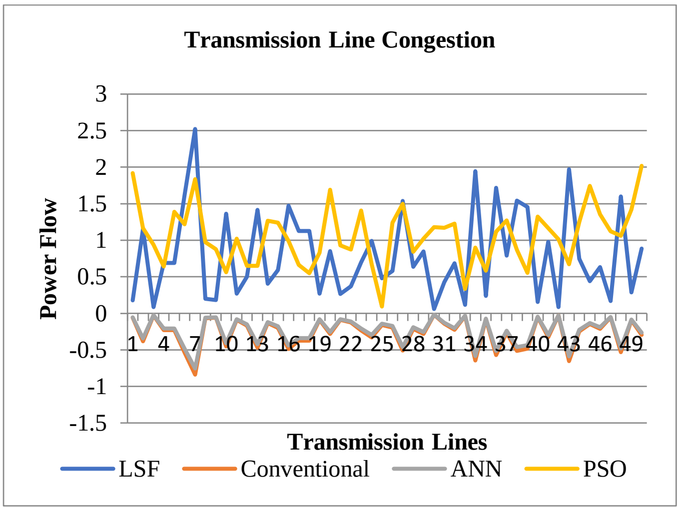

Figure 6. Transmission line Vs Power flow for Conventional, LSF, PSO and ANN methodologies representing congestion scenario

Table 7. 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

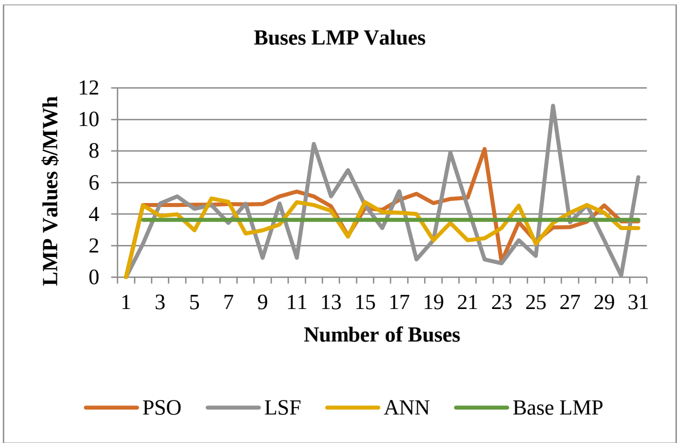

Figure 7. Bus LMP values for Conventional, LSF, PSO and ANN methodologies representing congestion cost estimation

Figure 7 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 7* statistically compares performance of the 3 methods for estimation of buses LMP values. *Table 8* shows RES curtailment percentage by all the 3 methods to manage the congestion and mitigate the congestion cost. The nest section discusses the results obtained for all the methodologies.

Table 8: 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

7. DISCUSSION and ANALYSIS

In results, *figure 6* 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 6* 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 7* and *table 8* 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.

8. CONCLUSION and FUTURE SCOPE

Figure 6 and 7 directs to exhaustive analysis for detecting congestion and congestion cost of the system as compared to the only conventional scenario depicting no congestion case. As discussed above, LSF method includes all the perspective of power system it is superior in reflecting the congestion of power lines. PSO and ANN methods depend on large number of historical data points of RES power output, filtration and fitting of data points hence, PSO fails to determine the exact power flow pattern for present scenario. The LMP of buses depends on number of factors as location of RES generation, output of RES generation, power flow within the lines. Hence, ANN proves to be more efficient as compared to remaining 2 methods.

LSF being deterministic in nature predicts a higher value of LMP irrespective of close reflection of power flows in the lines. Although from statistical parameters LSF is considerably superior to PSO but less effective when compared to ANN as it lacks self-learning characteristics.

It can be understood that LSF can be applied to power system during planning process. Whereas PSO and ANN are more approachable methods during operation periods of power system as they require large number of data values to improve their performance to mange and relieve congestion with minimized congestion cost and utmost utilization of RES power output with less curtailment.

The analysis can be extended further for different RES sources and a wide prsctical electrical network. ANN methodology can be implemented to have pattern recognition as well as prior estimation of congestion into the system.

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