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Sensitivity factors based computationally efficient approach for evaluation and enhancement of available transfer capability

Manjula S. Sureban, Shekhappa G. Ankaliki
Department of Electrical and Electronics Engineering, Shri Dharmasthala Manjunatheshwara College of Engineering and Technology, Dharwad, Affiliated to Visvesveraya Technological University, Belagavi, India

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ABSTRACT

Available transfer capability (ATC) is an indication of the capability of the transmission system to efficiently increase power transmission for further commercial trading between two areas or two points. ATC plays an important role in operating power systems economically, reliably, and securely. As the deregulation in the power system can cause overload in the transmission system, ATC evaluation and enhancement are required for secure and reliable operation. The advancements in power generation techniques and switching from centralized generation to distributed generation (DG) with more emphasis on renewable sources have resulted in various approaches to enhance ATC. In this work, a computationally efficient sensitivity-based methodology for evaluating and improving ATC with the presence of renewable generation is proposed. The developed approach is implemented on the IEEE 30 bus system and the outcome is compared with the existing methods in the literature.

Corresponding Author:

Manjula S. Sureban
Department of Electrical and Electronics Engineering, Shri Dharmasthala Manjunatheshwara College of Engineering and Technology, affiliated to Visvesveraya Technological University Belagavi
Belagavi, India
Email: smanjula845@gmail.com

1. INTRODUCTION

The deregulation of electric power systems resulted in many significant transformations in the real-time operation and control actions of power grids. With the increasing number of bilateral transactions, the possibility of insufficient transmission capability leads to network congestion. Also, operational and planning aspects of power systems pose some challenging problems in the deregulated power industry. In such a scenario, evaluation and improvement of the available transfer capability (ATC) of the transmission system become the most important issue. ATC estimates the transfer capability remaining in the transmission system for further commercial trading in addition to the already committed users. According to the North American Electric Reliability Council (NERC) [1], the total transfer capability (TTC) of the transmission system is known as the highest amount of power that can be transferred between two areas or zones or buses that does not result in overload of transmission line, violations in voltage limit at system buses and any other system security problems [1]. Mathematically ATC is defined as [2].

$$ATC = TTC - TRM - CBM - ETC \tag{1}$$

In (1), the transmission reliability margin (TRM) is the transfer ability of the transmission system required to ensure that the power system is secure during a certain range of uncertainties. Also, capacity benefit margin

(CBM) is the transfer capability reserved for load-serving systems to access generation reliability requirements. ATC is the existing transfer commitment.

ATC calculation is a complex task, especially in large deregulated systems. The incorrect estimation of ATC results in inefficient use of the transmission network. Accordingly, the error-free and efficient methodology for ATC determination is essential in today's power system framework. Researchers have developed various methods for the calculation and enhancement of ATC. Many authors in the literature have proposed continuous power flow and repeated power flow methods for the computation of ATC as they are mathematically less complex [3]. However, these techniques are more time-consuming [4]. The sensitivity-based fast computational methods using DC and AC power transfer distribution factors (PTDFs) [5] have been used for evaluating ATC by many researchers which can also be further extended to compute ATC during outages by computing line outage and generator outage distribution factors (LODF, GODF). These methods are faster compared to the continuous power flow (CPF) method and repeated power flow (RPF) method [6]; however, these are based on assumptions. Some researchers have formulated the evaluation of ATC as an optimization problem and then different optimization techniques are used to evaluate the same. The hybrid grey wolf flower pollination algorithm (HGWFPA) method can be used to optimize the ATC in the transmission system which is the hybridization of grey wolf optimization (GWO) and flower pollination algorithm (FPA). The HGWFPA method gives better results for ATC than the GWO and FPA method [7].

ATC of a system can be enhanced using flexible AC transmission system (FACTS) devices. Researchers employ various techniques to ascertain the optimal value and placement of FACTS devices, such as the static var compensator (SVC) and thyristor-controlled series compensator (TCSC). The adaptive Moth Flame optimization technique which is the adoptive version of the moth flame algorithm can be used to evaluate and enhance ATC in the presence of TCSC. This algorithm resulted in a better response regarding the enhancement of ATC against the particle swarm optimization (PSO) and bacterial swarm optimization (BSO) [8] techniques. Durković and Savić [9] presented the method for ATC enhancement using the TCSC device in case one out of two announced transactions is canceled. This research evaluates ATC by taking into account common uncertainties that are required while planning a power system over a longer period of time. In the paper [10], the enhancement of ATC of a deregulated power network is obtained by incorporating SVC and TCSC models in Newton Raphson load flow equations. In this paper, minimization of real power losses and improvement in voltage profiles at all buses are considered as objectives for ATC evaluation.

ATC of a system can also be enhanced by using renewable generation. In the paper [11], a sensitive-based formula is used to find the optimal buses for the location of wind generators. The transmission congestion distribution factor (TCDF) is used to create the zones for assessing ATC. The suitable location for the system to integrate wind DG to improve ATC is determined by the average transmission congestion distribution factor (ATCDF). The paper [12] demonstrates the performance of TCSC in enhancing the ATC based on different methods of placements. Real power performance index, real power loss sensitivity with respect to the line reactance where TCSC is placed and power transfer distribution factor are considered for choosing the optimal location of TCSC. The optimal location for the TCSC is found by using each of these techniques separately, and the associated ATC values are calculated. ATC improvement varies from 2% to 85%, and real power loss minimization can reach 25% depending on placement techniques used. Also, the importance of ATC evaluation by incorporating renewable energy generation is addressed in this paper. The paper [13] proposes an algorithm to find the suitable location and size of TCSC device by maximizing ATC and minimizing power losses. Also, the algorithm reduces the installation cost of the TCSC device. Paper [14] presents the application of TCSC to improve the transfer capability of a power system by considering the reactive power flows in ATC computations. The computation of transfer capability also depends on the type of the load. The impact of load variation can be considered for the exact evaluation of ATC. Hence, the impact of the general load model is considered as ZIP load along with constant power loads in [15].

Many researchers have addressed the importance of evaluating the exact value of ATC in the present deregulated system at a faster rate and enhancing using FACTS. An attempt is made in this work to compute the accurate value of ATC at a faster rate with reduced computations using dominating PTDFs and the results are compared against those obtained using DC power transfer distribution factor (DCPTDF) and repeated power flow (RPF) method. Also, a sensitivity-based formula is used for choosing the suitable location of DG to improve ATC. The proposed methodology is implemented on the IEEE 30 bus system.

2. ATC CALCULATION METHODS

As energy regulatory commissions provided open access to the transmission network, large-scale power transactions between utilities have increased rapidly. Also, the transactions between areas and buses are continuously increasing as the power demand is increasing. Because of this the transmission network is highly congested and system limits are violated which results in the insecure operation of the power system. The evaluation of ATC plays an important role in guiding deregulated market participants to carry out bilateral transactions without affecting system security. Various methods are proposed in literature to calculate ATC. These methods are categorized into four types: i) repeated load flow (RPF) method, ii) linear approximation method, iii) optimal power flow (OPF) method, and iv) based on a probabilistic approach.

2.1. Repeated power flow technique (RPF)

In the RPF method, ATC is evaluated by performing power flow analysis repeatedly [16] until system limits are violated. In this method, one pair of sources and sink buses are chosen then real power injection at the source bus is increased and the equal amount of real power demand at the sink bus is increased in regular steps. The load flow analysis is performed and bus voltages and line loadings are observed in every step. The process of repeatedly performing load flow is continued until any one line in the system reaches its maximum loading limit. On reaching the limit, the power flow analysis is stopped. The source bus's power injection for the last step is noted down. If P_{lmax} represents the power injection at the source bus when the maximum limit is attained and P_{base} represents real power at the same bus for the base case, then ATC is calculated using (2).

$$ATC = P_{lmax} - P_{base} \quad (2)$$

2.2. Linear approximation method (LAM)

In LAM, the ATC of a highly interconnected system is obtained by calculating sensitivity factors for the given network topology. The power transfer distribution factor (PTDF) is used to find the incremental distribution of power flows corresponding to transactions between two areas/busses/regions [17]. Two types of PTDF are used for evaluation of the ATC of the system viz. AC-PTDF and DC- PTDF. In the AC-PTDF method active along with reactive power flows are considered in the computation of ATC whereas in DC-PTDF only active power flows are considered. Even though AC-PTDF gives better results in comparison with DC-PTDF, it is complex because of more computations and also time-consuming because of the implementation of complete AC power flow for each generator outage contingency analysis. Therefore DC-PTDF method is more commonly used to calculate ATC.

2.2.1. DC PTDF method

PTDF is a fraction of the transaction from seller to buyer that flows through a given transmission line [18]. Symbolically $PTDF_{ij,mn}$ is a fraction of a transaction from source bus 'm' to sink bus 'n' that flows through a transmission line from bus 'i' to bus 'j'. The formula for calculating PTDF is mentioned in (3).

$$PTDF_{ij,mn} = \frac{X_{im}-X_{jm}-X_{in}+X_{jn}}{x_{ij}} \quad (3)$$

In (3), x_{ij} represents the reactance of transmission line connecting the buses i and j. X_{im}, X_{jm}, X_{in} and X_{jn} are the elements of the bus sensitivity matrix or reactance matrix obtained from the bus admittance matrix. Once the PTDFs are calculated, the total transfer capability (TTC) of a line connecting i-j is computed using (4),

$$T_{ij,mn} = \begin{cases} \frac{P_{ij}{}^{max} - P_{ij}{}^{0}}{PTDF_{ij,mn}} & ; \quad PTDF_{ij,mn} > 0 \\ \frac{-P_{ij}{}^{max} - P_{ij}{}^{0}}{PTDF_{ij,mn}} & ; \quad PTDF_{ij,mn} < 0 \\ \infty & ; \quad PTDF_{ij,mn} < 0 \end{cases} \quad (4)$$

In (4), $P_{ij}{}^{max}$ is the thermal constraint of line connecting bus i and j, $P_{ij}{}^{0}$ is the base case power flow through a line connecting bus i and j. The line with minimum transfer capability is called a constraining branch which decides the ATC of the system. Finally, the ATC of the system is computed by using (5).

$$ATC = min\,\{T_{ij,mn}\} \quad (5)$$

2.2.2. Proposed approach using dominating PTDF

It is observed from existing literature that AC-PTDF and DC-PTDF methods are mathematically complex, especially for large interconnected systems. This is because these methods require computation of transfer capabilities for all the lines and then finding the minimum of these as ATC [19]. This makes the process complex and time-consuming. Also, when a power system operator is required to decide to allow participants in the deregulated market to sell or buy power quickly, it would be difficult resulting in congestion in transmission lines. To overcome such problems, a computationally efficient approach using only dominating PTDF is proposed for the computation of ATC in this paper. In this approach PTDFs are calculated for all lines for all required transactions (seller-buyer pair), their absolute values are considered and 40% of the total lines with higher absolute PTDF are considered for computation of ATC of a system. This is true because, when lines with the lower value of absolute PTDFs are used in evaluating transfer capability, it results in a large value of TTC from (4). Such lines when compared with others to choose minimum, obviously they are discarded. Therefore, in this proposed method for a given system topology and the required pair of transactions, dominating PTDFs are calculated and stored as standard data. During the time of evaluation of ATC, the power flow analysis is carried out and transfer capability is evaluated for only those lines having dominating PTDF and corresponding ATC is noted down.

Steps involved in dominating -PTDF approach:

Step 1: Dominating PTDFs are calculated using (3) for a given system topology, also for possible bilateral transactions, and are made available for further use.

Step 2: Power flow analysis is carried out for the system during particular conditions and checked against the system constraints. Power flows through transmission lines are noted.

Step 3: Transfer capabilities are calculated using (4) for only those lines having high PTDF as obtained in step 1.

Step 4: ATC for a particular condition is obtained by choosing the minimum value of transfer capability.

3. MODELING AND OPTIMAL LOCATION OF DG

ATC of a given system can be enhanced with distributed energy generation (DG). The distributed generations mainly include nonconventional energy resources like solar, wind, biomass, and hydropower. These generation plants are usually installed at the load centers depending upon the availability of resources and utilized for local needs. DGs are substitutes for new transmission lines to meet the increasing demand. In this paper, the use of solar and wind generators to enhance the ATC is demonstrated.

3.1. Modeling of photovoltaic DG

Photovoltaic (PV) systems are either grid-connected or stand-alone. The electric current resulting from the PV cell is direct. Therefore, power generated by PV cells is always DC power and needs to be converted into AC before connecting to the grid. Different topologies of inverters are used to convert DC power from the PV system into AC which also takes into account voltage and frequency match. In this study, PV-DG is modeled as a real power generator [20] at load buses whose output varies with solar irradiance. The output power from the PV system is given by (6).

$$P_{pv} = \begin{cases} P_{pvr} \times \left(\frac{G}{G_0}\right) & 0 \le G \le G_0 \\ P_{pvr} & G_0 \le G \end{cases} \tag{6}$$

Here P_{pvr} is the rated output power of the PV system at standard conditions (solar radiation=1000 W/m^2 and temperature=25 °C). Also, G and G_0 are the solar radiation (W/m^2) for the selected location and rated radiation on earth's surface ($1000\ W/m^2$) respectively.

3.2. Wind generation modeling

The wind generator (WG) produces AC power and can be connected to the grid at medium or high voltage levels. In this study, WG is modeled as a real power generator [21], at load buses whose output varies with wind speed. The output power from WG is given by (7).

$$P_w = \begin{cases} 0 & 0 \le V \le V_{ci} \\ P_r \frac{V - V_{ci}}{V_r - V_{ci}} & V_{ci} \le V \le V_r \\ P_r & V_r \le V \le V_{co} \\ 0 & V_{co} \le V \end{cases} \tag{7}$$

Here V is the wind speed, V_{ci} is the cut-in speed, V_{co} is the cut-out speed and V_r is the rated speed. P_r represents the rated power output of WG.

3.3. Optimal location of DGs

Even though solar photovoltaic DG and wind DG are available in larger capacities and all locations, their uses are limited by some important challenges. Solar PV DG is an intermittent source available on sunny days and wind DG is available only when wind speed is more than its cut-in speed. Also, the connection of multiple DGs of inappropriate size and at incorrect locations leads to a reverse flow of power as well as increased system losses. It also results in the uneconomical operation of the system. This issue of finding the correct size of DG at an optimal location with the system losses [22] is addressed in this paper by finding the real power loss reduction sensitivity factor (PLRSF) given by (8).

$$\text{PLRSF} = \frac{P_{\text{loss with DG}} - P_{\text{loss base}}}{P_{\text{DGi}}} \tag{8}$$

Here, P_{DGi} is the size of the DG placed at load bus i, $P_{loss\ base}$ is the initial power loss in the system, $P_{loss\ with\ DG}$ is the power loss after placing DG. If the PLRSF value is strictly negative as the system losses are reduced after placement of DG, else the DG integration is not suggested. Therefore, the bus having a large PLRSF value is selected as the optimal location for DG placement.

4. CASE STUDY

In this study, the IEEE 30 bus system [23] is considered for ATC evaluation by RPF, PTDF, and the dominating PTDF method. This system has six generators and twenty-one loads with four transformers and two shunt capacitors. Also, to determine the ATC of the test system under different loading conditions over 24 hours, a sample load duration curve shown in Figure 1 is considered. Even though the base case load is 283.4 MW, over 24 hours the load on the system varies from 256 to 312 MW.

4.1. DG considerations

In this proposed work, the rated power of solar DG considered is 25 MW, at a rated irradiance of 1000 W/m^2. The sample variation of solar irradiance in W/m^2 over 24 hours is shown in Figure 2. The power output from solar DG for 24 hours is calculated and tabulated in Table 1. The rated power output of wind DG considered is 30 MW, at a rated wind speed of 35 km/hr. The cut-in and cut-out speeds of wind are 20 km/hr and 50 km/hr respectively. The sample variation of wind speed in km/hr over 24 hours is shown in Figure 3. The output power from wind DG for over 24 hours is calculated using (7) and tabulated in Table 2.

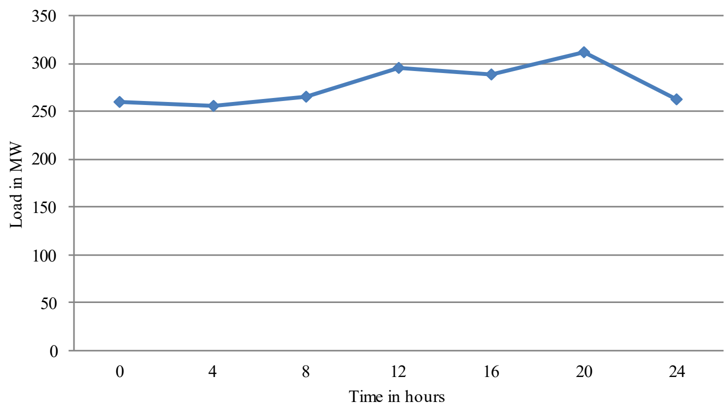

Figure 1. Daily load duration curve

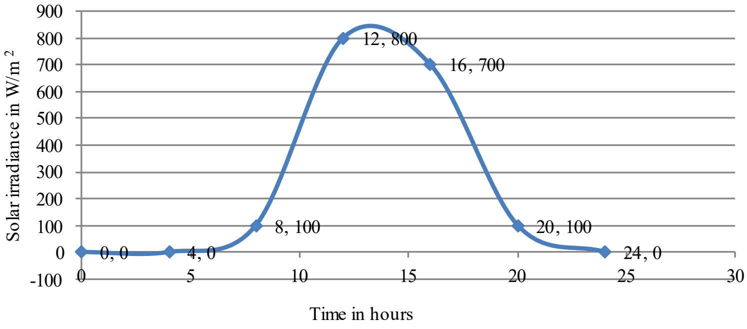

Figure 2. Sample data of solar irradiance over a period of 24 hours

Table 1. Solar DG output over 24 hours

Time in hours	Solar irradiance W/m2	Power output in MW
0	0	0
4	0	0
8	100	2.5
12	800	20
16	700	17.5
20	100	2.5
24	0	0

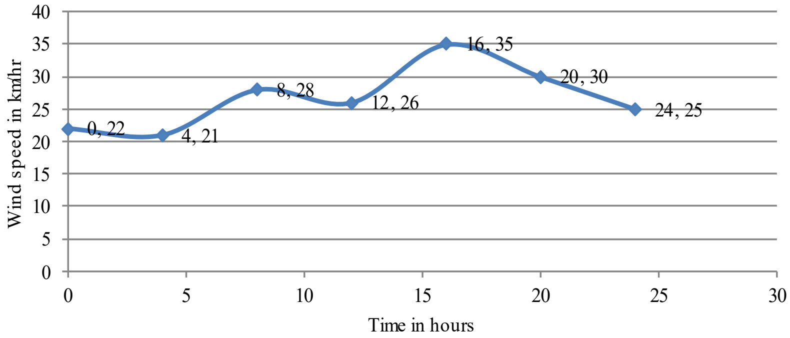

Figure 3. Sample data of wind speed over a duration of 24 hours

Table 2. Output power from wind DG

Time in hours	Wind speed in km/hr	Power output in MW
0	22	4
4	21	2
8	28	16
12	26	12
16	35	30
20	30	20
24	25	10

5. RESULTS AND DISCUSSION

5.1. ATC results in comparison using DC-PTDF, dominating PTDF and RPF methods for the base case

ATC values are obtained for the IEEE 30 bus system using DC-PTDF method using MATLAB and here PTDF values are calculated every time, then the corresponding transfer capabilities are evaluated for all lines to obtain a minimum one as ATC and the time taken for computation is noted. Also, ATC values are obtained for the system using only dominating PTDFs using MATLAB, and time taken is noted. Here time for computation is noted down using the same PC with particular specifications and time taken in both cases is compared. Finally, the ATC values obtained by these methods are validated using RPF method using the power world simulator [24].

It is observed from Table 3 that ATC values obtained by using all PTDF and using only dominating PTDF are the same, but the time taken for computation is more if all PTDFs are used. Also, the ATC values obtained using RPF method from the power world simulator are comparable with that of the dominating PTDF method. Therefore, in this paper for all further analysis dominating PTDF method is used which is computationally efficient and accurate.

Table 3. ATC in MW using different methods and time taken for computation

Source Bus	Sink Bus	DC PTDF Method		Dominating PTDF		RPF method ATC in MW
		ATC in MW	Time taken in	ATC in MW	Time taken in	
2	8	5.6305	seconds	5.6305	seconds	4
2	21	10.7321	is 0.020	10.7321	is 0.0011	12
2	24	16.3289	Say T1	16.3289	0.05*T1	15

5.2. ATC results for sample load profile

The ATC values are evaluated using dominating PTDF method by considering sample load profile and are tabulated in Table 4. It is observed that the ATC at 0:00, 4:00, 8:00, and 24:00 hour is more than the base case therefore no need to enhance. Whereas at 20:00 hour, since the loading is nearly 110%, ATC is negative indicating that, the lines are highly congested which is a rare case in power system operation. However, ATC has to be enhanced at 12:00 hour as the loading is nearly 104% at this time and ATC is less than the base case ATC for all transactions.

Table 4. ATC in MW for different durations in a day from 00 to 24 hours

Source Bus	Sink Bus	0:00	4:00	8:00	12:00	16:00	20:00	24:00
		91%	90%	93%	104%	102%	110%	92%
2	8	10.9190	12.0882	8.0784	2.34	3.4849	-4.3836	10.9203
2	21	18.1822	20.1776	14.5890	6.2831	7.6558	-98.384	18.2066
2	24	19.7421	20.2174	19.9707	13.2530	15.6816	-49.51	19.7393

5.3. ATC Enhancement using DG

5.3.1. Computation of PLRSF for all load buses

As the ATC has to be enhanced at 12:00 hour the output power of the solar DG at this time is 20 MW and that of wind DG is 12 MW from Table 1 and 2 respectively. To find the optimal location of these DGs, the real power loss reduction sensitivity factor (PLRSF) is computed by placing 20 MW and 12 MW DG at all load buses and is tabulated in Table 5. It is observed that bus number 23 is the suitable location for placement of solar DG and bus number 30 is for wind DG as they result in the least power losses with larger PLRSF. Finally, the ATC is computed at peak load with and without DG at the chosen location and tabulated in Table 6. It is observed that the ATC values are enhanced in the presence of DGs. Table 7 shows that the proposed approach of evaluating ATC and improving the same with optimally placed DG by using sensitivity factor gives better results in comparison with other methods in the existing literature.

Table 5. Real power loss reduction sensitivity factor (PLRSF) with DG at load buses

Load Bus number	With 20 MW DG at all load buses			With 12 MW DG at all load buses		
	Power loss in MW	PLRSF	Rank	Power loss in MW	PLRSF	Rank
3	15.970	-0.0779	20	16.565	-0.0802	20
4	15.486	-0.1021	15	16.273	-0.1046	18
5	14.633	-0.1447	2	15.785	-0.1439	2
7	14.818	-0.1355	3	15.851	-0.1397	3
8	15.041	-0.1243	7	15.989	-0.1282	11
10	15.152	-0.1188	11	16.058	-0.1225	14
12	15.516	-0.1006	17	16.277	-0.1042	19
14	15.500	-0.1014	16	16.185	-0.1119	16
15	15.145	-0.1191	12	16.029	-0.1249	12
16	15.588	-0.1070	18	16.162	-0.1138	17
17	15.175	-0.1176	13	16.051	-0.1231	13
18	15.076	-0.1226	9	15.939	-0.1324	9
19	14.997	-0.1265	6	15.892	-0.1363	4
20	15.051	-0.1238	10	15.936	-0.1327	8
21	14.958	-0.1285	4	15.921	-0.1339	7
23	**14.565**	**-0.1481**	**1**	15.921	-0.1339	6
24	14.995	-0.1266	5	15.901	-0.1356	5
26	15.872	-0.0828	19	16.169	-0.1132	15
29	15.328	-0.1100	14	15.964	-0.1303	10
30	15.092	-0.1218	8	**15.782**	**-0.1455**	**1**

Table 6. ATC at peak load without and with DG

Source Bus	Sink Bus	ATC in MW without DG	ATC in MW after Placing DG at optimal location		
			Only solar DG at bus number 23	Only wind DG at bus number 30	With both DGs
2	8	2.34	4.1144	7.4646	4.5949
2	21	6.2831	8.0025	12.2796	22.8435
2	24	13.2530	16.4040	16.2423	20.8837
2	28	9.0358	11.5546	17.4475	19.7174

Table 7. Comparison of results with existing literature for different transactions concerning the IEEE 30 bus system

Reference	Seller and Buyer pair	Type of device/system used for enhancement	Methodology for optimal location	ATC in MW without a device/system	ATC in MW with device/system	Increase in ATC in percentage
[25] Year 2024	2-28	STATCOM	Whale optimization algorithm	112.1	218.03	94.496
[26] Year 2022	2-26	TCSC	TLBO Optimization algorithm	12.18	14.53	19.239
	2-5			116.65	125.13	7.2696
[27] Year 2011	2-28	TCSC	Particle swarm optimization	24.821	27.614	11.25
		SVC		24.821	25.413	2.3851
		UPFC		24.821	31.004	24.9104
Proposed Work	2-8	Solar DG	Loss reduction sensitivity factor	2.34	4.1144	75.8291
		Wind DG		2.34	7.4646	219
	2-28	Solar DG		9.0358	11.5556	27.8869
		Wind DG		9.0358	17.4475	93.093

6. CONCLUSION

The evaluation and enhancement of available transfer capability serve as a tool to solve the problem of network congestion arising due to deregulation in today's power industry. This work presents a computationally efficient method for the computation of ATC for a given system under different loading conditions. Also, this paper presents an approach for placing the appropriate size DGs at a suitable location in the system to enhance ATC. As the power system is moving from centralized to distributed generation these days, the advantage of having DGs in the system to improve ATC is a novel approach compared to the one using FACTS. The impact of increasing the number of DGs and the size of DGs on ATC is the next research question to be addressed. Also, the approach proposed can be further used in developing an intelligent system that estimates the ATC of a given system during existing loading conditions very quickly and also predicts the efficient transaction at a given operating condition to avoid network congestion and make the power system more reliable, economic and secured.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Manjula S. Sureban	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Shekhappa G. Ankaliki	✓	✓		✓	✓	✓		✓		✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

Ethical approval is not applicable as this paper as not talk about using people or animals.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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BIOGRAPHIES OF AUTHORS

Manjula S. Sureban holds a B.E. in electrical and electronics engineering and M.Tech. in electrical power system engineering. She is currently employed as an assistant professor in the Electrical and Electronics Engineering Department at SDM College of Engineering and Technology in Dharwad, Karnataka, India. She is pursuing Ph.D. at VTU, Belagavi. She has 8 years of teaching experience. Her area of research includes power system operation and control, electrical drives, FACTS and AI applications to power system. She has guided number of PG and UG projects. She has submitted number of research proposals to various funding agencies such as DST, SERB and VGST. She is a life member of the Institution of Engineers (India). She can be contacted at email: smanjula845@gmail.com.

Shekhappa G. Ankaliki received his B.E. degree in electrical and electronics engineering, M.Tech. degree in power system engineering from Mysore University, Mysore, Karnataka, India. He received his Ph.D. degree in 2011 from Visvesvaraya Technological University, Belagavi, Karnataka, India. He worked as a faculty of Electrical and Electronics Engineering Department at Hirasugar Institute of Technology, Nidasoshi. Currently he is working as a professor and head of the department of Electrical and Electronics Engineering, SDM College of Engineering & Technology, Dharwad. He is having 33 years of teaching experience and published more than 95 technical papers in various international and national journals and 70 papers in conference proceedings. He is a member of MIE, and ISWE. His current research areas include intelligent techniques for power system operations, power system security, distribution system service restoration, distribution system automation and distributed generation resources for power system. He can be contacted at email: sgasdmee@rediffmail.com.