Research Article

A novel sensitive based approach to ATC enhancement in wind power integrated transmission system

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Abstract

Available transfer capability (ATC) plays an important role for both buyers and suppliers in the deregulated power system. As the integration of renewable energy sources is taking place very quickly in the system. It is not suggested to place wind generation (WG) at any point of the system. In this paper, the optimal location of buses for WG using a novel sensitive based formula is proposed. The zones are formed using the transmission congestion distribution factor (TCDF) values. The average transmission congestion distribution factor (ATCDF) is used to locate the optimal point of the system. When the WG is integrated into the system its obvious ATC increases but at which point the ATC values will be more is considered as the main objective. The WG is placed at every bus in the zone created by the TCDF value and the ATC value is calculated. The test is performed on the IEEE-30 bus system in MATLAB coding environment. The comparison result shows the ATC value enhances more when the WG is placed according to the proposed method. The proposed method also helps to find multiple locations for WG installation according to ATCDF value.

Highlights

- Average TCDF value is proposed to find the optimal bus location for getting more ATC value.
- Integration of WG according to highest ATCDF value in the system.
- Comparison of ATC obtain from the integration of WG at different buses in sensitive zones.
- Validation of a proposed method by comparing the ATC value obtain from integrating WG at different buses.
- The optimal bus location based on the ATCDF value gave enhance ATC value compare to the other bus location.
- ATCDF value helps in finding the multiple locations for integration of WG in the system.

Abbreviations and List of symbols

ACPTDF	AC power distribution factor	TCDF	Transmission congestion distribution factor
ATC	Available transfer capability	ATCDF	Average TCDF
WF	Wind firm	RACPF	Repeated alternating current power flow
FACTS	Flexible AC transmission system	LRA	Low-rank approximation
PDF	Probability distribution factor	TCSC	Thyristor controlled series compensator

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HGWFPA	Hybrid grey wolf optimization and flower pollination algorithm
RGA	Real genetic algorithm
AHP	Analytical hierarchy process
PSO	Particle swarm optimization
SVC	Static VAR compensator
UPFC	Unified power flow controller
CSA	Cuckoo search algorithm
HEPF	Holomorphic embedding power flow
IPFC	Interline power flow controller
VSC-OPF	Voltage-stability constrained optimal power flow
SPCR	Sensitivity and power loss-based congestion reduction
MEEPSO	Metaheuristic evolutionary particle swarm optimization
SSSC	Static synchronous series compensator
θ_{ab}	The angle between bus voltage
P_{ab}^{max}	The thermal limit of the line between buses a and b
v	Speed of the wind
P_{ab}^0	Base case power flow between buses a and b
ΔP_{mn}	Change in power in line k connecting between bus m and n
ATC_{mn}	Available transfer capability in MW
$TCDF_1$	TCDF value for one congested line
N	Number of the congested line due to line outage
Δtr_{mn}	Power transaction in MW
(ΔP_m)	Change in the active power at bus m
$f_v(v)$	Wei-bull probability function
N_L	Total number of lines
$P_{r,i}$	Rated power capacity of wind turbine
Δqu_l	Change in the transmission line quantity
$T_{ab,mn}$	The transfer Power value of each line during the transaction
U_a	Bus a voltage
Y_{ab}	Admittance Matrix

1 Introduction

Energy demand is exponentially increasing, and conventional energy supplies are gradually decreasing. It is therefore important to make effective use of power system operations in such a way that their environmental impact can be minimized. Considering all these problems developed nations started to deregulate in operations of the power system. As a result of deregulation, competition in the power sector was established [1].

In deregulated power system available transfer capability (ATC) play an important role in power transaction and system stability analysis. Available transfer capacity

for power systems is the transfer capacity remaining in the physical transmission network for further commercial activity, over and above that already committed. State of art by researcher and comprehensive study about the ATC calculation is highlighted [2]. The concept of a repeated alternating current power flow (RACPF) approach for the calculation of ATC has been described. Inter-area line outage and generator outage condition for contingency analysis on IEEE-30 bus system are considered [3].

Electrical utilities require transmission system ATC information to be posted so that such essential data can help power marketers, distributors, and consumers in the plan, operate, and reserve transmission services. ATC is additionally useful data for the operator to see how far the limits are from the point of work and can also show an exchange limit that can be extended without compromising framework security and stability. A novel way of the probabilistic approach using canonical low-rank approximation (LRA) for ATC calculation is discussed [4]. ATC is the remaining transfer capability for further commercial activities in a physical transmission network well beyond the already committed usages. As a result, ATC describes the transfer capability margin throughout the system and plays an essential part in calculating the amount of power transferred through the transmission system to avoid congestion, ensure security, efficiency, safety, and other system reliability violations. The generator participation factor approach has been discussed to calculate ATC [5].

Due to the deregulation of power system operations, a competitive and innovative electricity market is being developed that promotes alternative energy generation methods such as wind, hydro, solar, etc. Wind energy is the fastest-growing renewable energy source because of its clean and inherent nature, Under the power market environment, the operation and planning of power systems should take into account both reliability and economic performance, which may be affected due to the integration of wind power. In reference [6], Short and medium-term reliability analyses are made with high wind power penetration. An analytical approach for the modelling of large wind farms (WFs) with reliability is presented in reference [7].

A lot of research has been done on the ATC model and calculation to reduce congestion. A brief survey has been done on an optimization algorithm, ATC calculation, and congestion management in reference [8]. The research work has rarely been studied on the ATC model and calculation concerning wind turbines connected to the electrical system. An effective method of ATC calculation for power systems containing wind generation must be developed [9].

ATC calculation can be divided into two categories i.e., repeated Newton Raphson power flow (NRPF),

continuation PF, fast decoupled power flow (FDPF), optimal power flow (OPF), RACPF, LRA, and power transfer distribution factor (PTDF), etc. are considered in group one whereas machine learning and optimization based technique are included in group two. There are many techniques and methods is used for ATC enhancement. In this comparative study, only those papers are considered which shows the enhancement of ATC in IEEE-30 bus given in Table 1.

In the literature, several methods have been discussed for the optimal location of FACTS devices. The real power performance indexed, total real power loss, transmission line thermal limit, base case limiting element, PTDF, real power loss w.r.t line reactance, least bus voltage magnitude, congestion rent contribution, generator participation factor, and least values of ATC are frequently used for selection of optimal location. In this paper, the novel average TCDF (ATCDF) value is proposed to find the optimal location of a bus in a zone for wind generator (WG) integration.

The contribution of the work includes the ATC calculation by integrating the WG at every bus. Before that, the zones are created using TCDF values by creating a line outage, and then the ATCDF value is calculated. The novel proposed work gives the result that enhances the ATC in a significant amount. As to find an optimal location, no optimization technique has been used so the proposed novel work reduces the time of computation and complexity of system simulation. As per the author's knowledge, there is no work has done considering the optimal location of WG for ATC enhancement.

This main organization of this paper is as the section I has introduction and literature survey part, Section 2 shows the methodology of ATC calculation by sensitivity-based AC power distribution method. Wind power output calculation with the relevant formula shown in Section 3. The proposed methodology has been discussed in Section 4. ATC calculation and variation using the proposed method considering optimally located wind power generation have been discussed in Section 5. The conclusions are given in Section 6.

2 ATC calculation methodology

There are several different ATC calculation approaches, such as DC power flow approach, sensitivity-based approach, FACT devices integration, optimum power-based approach, etc. [10–13].

let a change in real power generation for a specific transaction in between seller bus m and buyer bus n is Δtr_{mn}MW and this resulted in a change in real power flow

Δqu_lMW for the interconnected transmission line a and b. hence, ACPTDF is presented as Eq. (1)

$$ACPTDF_{ab,mn} = \frac{\Delta qu_l MW}{\Delta tr_{mn} MW} \tag{1}$$

Δqu_l MW is the change in the transmission line quantity either from a to b or from b to a. $ACPTDF_{ab,mn}$ the factor is deciding factor of the system. The higher value of $ACPTDF_{ab,mn}$ means that the ATC value of that bus of the system will be more. That means the line is approaching its decided limitation. This higher value of ACPTDF also indicates if there is a further increase in power flow then the line will create congestion in the system.

The above power changes are calculated from the base case, load flow results evaluated by the Newton Raphson Jacobian matrix. The change in active power w.r.t the state variable is given by Eqs. (2) and (3) respectively.

$$\frac{\partial P_{ab}}{\partial U_k} = \begin{cases} 0; & k \neq a,b \\ 2U_a Y_{ab} \cos(\theta_{ab}) - U_b Y_{ab} \cos(\delta_a - \delta_b - \theta_{ab}); & k = a \\ -U_a Y_{ab} \cos(\delta_a - \delta_b - \theta_{ab}); & k = b \end{cases} \tag{2}$$

$$\frac{\partial P_{ab}}{\partial \delta_k} = \begin{cases} 0; & k \neq a,b \\ U_a U_b Y_{ab} \sin(\delta_a - \delta_b - \theta_{ab}); & k = a \\ -U_a U_b Y_{ab} \sin(\delta_a - \delta_b - \theta_{ab}); & k = b \end{cases} \tag{3}$$

$$\Delta P_a = +\Delta tr_{mn} MW \tag{4}$$

$$\Delta P_b = -\Delta tr_{mn} MW \tag{5}$$

where $+\Delta tr_{mn}MW$ is seller bus transaction and $-\Delta tr_{mn}MW$ indicates the buyer bus of the transaction given by Eqs. (4) and (5). ATC is calculated at base case, between bus m and n for ACPTDF condition. Equation (6) shows the ATC calculation formula in the transmission line. The minimum value decides the limit point and gives the desire ATC value of the sensitive line given by Eq. (7).

$$T_{ab,mn} = \begin{cases} \frac{(P_{ab}^{max} - P_{ab}^0)}{ACPTDF_{ab,mn}}; ACPTDF_{ab,mn} > 0 \\ \propto (Infinite); ACPTDF_{ab,mn} = 0 \\ \frac{(-P_{ab}^{max} - P_{ab}^0)}{ACPTDF_{ab,mn}}; ACPTDF_{ab,mn} < 0 \end{cases} \tag{6}$$

$$ATC_{mn} = min\{T_{ab,mn}\}, ab \in N_L \tag{7}$$

where $T_{ab,mn}$ Is transfer Power value of each line during the transaction, P_{ab}^{max} is the thermal limit of the line between buses a and b, P_{ab}^0 is Base case power flow between buses a and b, $ACPTDF_{ab,mn}$ calculate AC Power

transfer distribution factor, ATC_{mn} denotes Available transfer capability in MW for line violating the limits and N_L are the Total number of lines.

3 Wind power generation

There is a various factor such as geography and topology which affect the wind characteristics. It can be estimated by observing the frequency of the wind speed. The characteristic of the variations in wind speed can be better understood by the distribution function of the Weibull probability, $f_v(v)$ with the shape factor k, the scale factor c, and wind velocity v m/s [14, 15]. the probability distribution factor (PDF) of wind speed at a given interval can be given by Eq. (8)

$$f_v(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{(k-1)} e^{-\left(\frac{v}{c}\right)^k}, \quad 0 < v < \infty \qquad (8)$$

Wind speed depended on the output power of the wind turbine is presented by (9)

$$P_W = \begin{cases} 0 & 0 \le v_i \le v_{in,i} \\ P_{r,i} \frac{v_i - v_{in}}{v_{r,i} - v_{in,i}} & v_{in,i} \le v_i \le v_{r,i} \\ P_{r,i} P_{r,i} & v_{r,i} \le v_i \le v_{o,i} \\ 0 & v_{o,i} \le v_i \end{cases} \qquad (9)$$

where v_i is a wind speed of bus i, $P_{r,i}$ denote rated power capacity of a wind turbine, $v_{in,i}$ and $v_{r,i}$ is cut in rated speed and $v_{o,i}$ is cut out rated speed of wind turbine [16].

4 Proposed methodology

4.1 Zones/clusters concept using the average TCDF values

TCDF denotes the active power change (ΔP_{mn}) in line-k, connecting between bus-m and bus-n due to unit change in active power injection at bus-m (ΔP_m). Newton Raphson load flow Jacobian sensitivity is used to derive the TCDF formula. Two methods DC load flow and AC load flow method are used in [17]. In the paper, the AC load flow method is used to calculate the TCDF for the congested line to create zones given by Eq. (10).

$$TCDF_m^k = \frac{\Delta P_{mn}}{\Delta P_m} \qquad (10)$$

The TCDF value for the congested line is the same in magnitude and opposite in sign. When the power is injected to a positive TCDF value bus, the ATC value

decreases whereas power injection at negative TCDF value bus increases the ATC value in the limiting line. For ATC improvement the power must be integrated to the highest negative value.

When there will be a line outage some areas of the system become most sensitive, which is identified to form a zone. The zone is created according to the TCDF values. It is possible for one line outage condition there is N number of line become congested i.e.multiple congestions. For each congested line, the zones are formed according to TCDF values. The superpositioning of zones gives the final resulting zone for one line outage condition. The highest and unequal value of TCDF value is taken to form zone 1. So, this zone is the most sensitive zone for the transaction. The lower and similar value of TCDF is taken to form zone 2 and higher zone. Zone 3 and zone 4 are very less sensitive zones so did not take into consideration. Zone 2 less sensitive zone compare to zone 1 but for ATC evaluation its role is significant.

Since for one congested condition, some buses in the zone are having positive TCDF values and the same buses having the negative TCDF value for the second congested condition so it is difficult to find the optimal location of WG for ATC improvement.

$$ATCDF = \frac{TCDF_1 + TCDF_2 + \cdots TCDF_N}{N} \qquad (11)$$

where $TCDF_1$ = TCDF value for one congested line. N = Number of the congested line due to line outage.

The average TCDF (ATCDF) is proposed in this paper to find the optimal bus location for WG integration given by Eq. (11). The average absolute value of TCDF is used to calculate the ATCDF value. The highest value of ATCDF value will give the optimal location of WG for ATC enhancement.

It is obvious that integration of WG will enhance the ATC value in the limiting line but at which bus it should be integrated so that it will improve the ATC value highest is the main concern. The ATCDF value will give the optimal bus location at which integration of WG will enhance the ATC value more compare to other bus locations. Different objective suggests different bus location of WG, here in this paper selection of optimal bus for ATC enhancement in the limiting line is taken as the main objective. The WG can be installed on any bus but the main objective is to find which bus will give maximum ATC value enhancement compare to others.

The AC power transfer distribution factor (ACPTDF) approach has been considered for ATC calculation. The ACPTDF method is simple, quick, non-iterative, and takes less time for computing and therefore is adopted in this work. There is some step to be followed in the calculation of ATC i.e.

Table 1 Comparison of ATC enhancement method and technology used for IEEE-30 bus

References	Methods	Technology	ATC (MW)	
			Before	After
[18]	Sensitive based	Emergency demand response	34.47	41.12
[19]	Implementing 5-Thyristor Controlled Series Compensator (TCSC)	Hybrid Grey Wolf Optimization and Flower Pollination Algorithm (HGWFPA)	21.3	621
[20]	Implementing one static VAR compensator (SVC) and one TCSC	Hybrid Mutation Particle Swarm Optimisation (HMPSO)	89.164	113.7
[21]	Optimal location and capacity of TCSC	Real genetic algorithm (RGA) associated with analytical hierarchy process (AHP) and fuzzy sets	215.52	291.55
[22]	TCSC, SVC, unified power flow controller (UPFC)	Particle swarm optimization (PSO)	24.821 (single area)	30.938
			92.613 (multi area)	96.371
[23]	Sensitive factor approch	OPF and FACT controller (Static Synchronous Series Compensator (SSSC), STATCOM and UPFC)	19.35	19.4832
[13]	Incorporation of SVC	Using Newton Raphson and ACPTDF formula	162.11	184.99
[24]	Parameter optimization of UPFC	Cuckoo Search Algorithm (CSA)	60.855	69.145
[25]	Non-iterative	Holomorphic embedding power flow (HEPF)	0.907	0.907 (less time)
[26]	Optimal location of TCSC	Least bus voltage magnitude and real power loss values	162.11	184.96
[27]	Parameter optimization of Interline Power Flow Controller (IPFC)	PSO	758.2363	781.2232
[28]	Voltage-stability constrained optimal power flow (VSC-OPF)	Weighted sum approach and PSO	1.4956	1.69
[29]	Optimal location of FACTS by Sensitivity and Power loss-based Congestion Reduction (SPCR)	Metaheuristic Evolutionary Particle Swarm Optimization (MEEPSO)	DCPTDF	34.8% more
			ACPTDF	33.06% more

- Choice of the base case and Newton Raphson load flow calculation
- Line outage for TCDF calculation and zone formation
- Calculation of ATCDF for different buses in the zones
- Selection of optimal location based on highest values of ATCDF for maximum ATC value in limiting line
- Wind power integration on transmission bus decided by ATCDF value
- ATC calculation by ACPTDF method with WG integration
- Comparison of ATC value results obtain from integrating the WG at different buses
- The optimal location gives the maximum value of ATC enhancement compare to other location for the same given data input

5 Results and discussion

The test for load flow analysis, ACPTDF, ATCDF, and ATC calculation are performed on the modified IEEE-30 bus system. The data is taken from http://www.ee.washington.edu/research/pstca. The IEEE-30 bus consists of 6 generators, 41 transmission lines, and 24 load busses in the system. The total demand for the bus is 293.08 MW, which is met by 6 generators present in the system. Bus 1 is considered to be a slack bus with 1 PU voltage and 0° angle.

5.1 ATCDF calculation for clusters/zones

An outage of the line between bus 4 and bus 6 causes congestion in lines 1–2 and 2–6 which is a case of multiple congestions. The first case is the calculation of TCDF for congested lines 1–2 and the second case is a calculation of TCDF for lines 2–6. The TCDF value for congested lines 1–2 & 2–6 have been given in Table 2. The clusters/zones for congested line 1–2 and line 2–6 based on TCDF is shown in Figs. 1 and 2 respectively.

The final zone will be formed by superimposing the zones created by congested lines 1–2 and 2–6. The main objective is to find the optimal bus location to installed WG for the maximum enhancement of ATC in the limiting line. So, the positive value of TCDF is not preferred for integration. The bus with a negative value of TCDF is considered

Table 2 ATCDF value for different buses

Bus no.	Line 4–6 outage to create congestion in the system		To select an optimal location in the zone
	TCDF for congested line 1–2	TCDF for congested line 2–6	Average TCDF (ATCDF) = (|TCDF| + |TCDF|)/2
1.	0.451429986	0.296316434	0.37387321
2.	− 0.451429986	0.315348992	0.383389489
3.	− 1.66E−05	0.237259465	0.118638029
4.	− 0.104744465	0.223559259	0.164151862
5.	− 0.488282239	0.008369509	0.248325874
6.	− 0.449189506	− 0.315348992	0.382269249
7.	− 0.47042956	− 0.188857727	0.329643643
8.	− 0.45122861	− 0.315997429	0.38361302
9.	− 0.396918618	− 0.229483984	0.313201301
10.	− 0.368950413	− 0.183540818	0.276245616
11.	− 0.396918618	− 0.229483984	0.313201301
12.	− 0.215456835	0.039020258	0.127238547
13.	− 0.215456835	0.039020258	0.127238547
14.	− 0.24033903	0.012221665	0.126280347
15.	− 0.264547546	− 0.022038746	0.143293146
16.	− 0.282762509	− 0.054986438	0.168874474
17.	− 0.345455706	− 0.146100945	0.245778326
18.	− 0.309954679	− 0.082777762	0.19636622
19.	− 0.33518787	− 0.118732864	0.226960367
20.	− 0.344515188	− 0.135703598	0.240109393
21.	− 0.371721733	− 0.182162824	0.276942278
22.	− 0.370380009	− 0.180406785	0.275393397
23.	− 0.306752867	− 0.081007668	0.193880268
24.	− 0.36055573	− 0.160596736	0.260576233
25.	− 0.400999436	− 0.224260012	0.312629724
26.	− 0.409754376	− 0.22960663	0.319680503
27.	− 0.420821989	− 0.259916364	0.340369176
28.	− 0.449158392	− 0.311009852	0.380084122
29.	− 0.441601268	− 0.273167256	0.357384262
30.	− 0.456843497	− 0.282887185	0.369865341

for optimal bus location to WG integration in both zones. ATCDF value is considered for only having the negative sign of TCDF in both congested line cases. The opposite sign of TCDF value in two different lines congested case will not be considered for ATCDF consideration.

5.2 Optimal location of wind farm according to ATCDF value

After superposing the zones for congested lines 1–2 and lines 4–6, combined clusters are formed. The buses in combined zones are given in Table 3. Zone 1 is the most sensitive, so wind generation must be introduced in this zone to increase the ATC value in the lines. Since most of the buses already have a generator so based upon the highest ACPTDF value bus 28 in zone 1 and bus 30 in zone 2 is

found suitable for operation. The ATCDF helps in two cases when there is a need for the installation of multiple WG in a system or when one zone is not having a proper location due to any technical reason.

5.3 ATC calculation considering WG at different buses in zone 1

The real wind data at the location of 8.2649° N, 77.5668° E for power generation has been taken to simulate the result. The WG of capacity 50 MW is used which actual output power is 47.33 MW. The reactive power limit of the WG varies between − 52 MVAR to 23 MVAR. The reactive power varies within the capability curve limit of wind turbines during the simulation. The bilateral transition between bus 6 and bus 28 is considered for ATC calculation. The
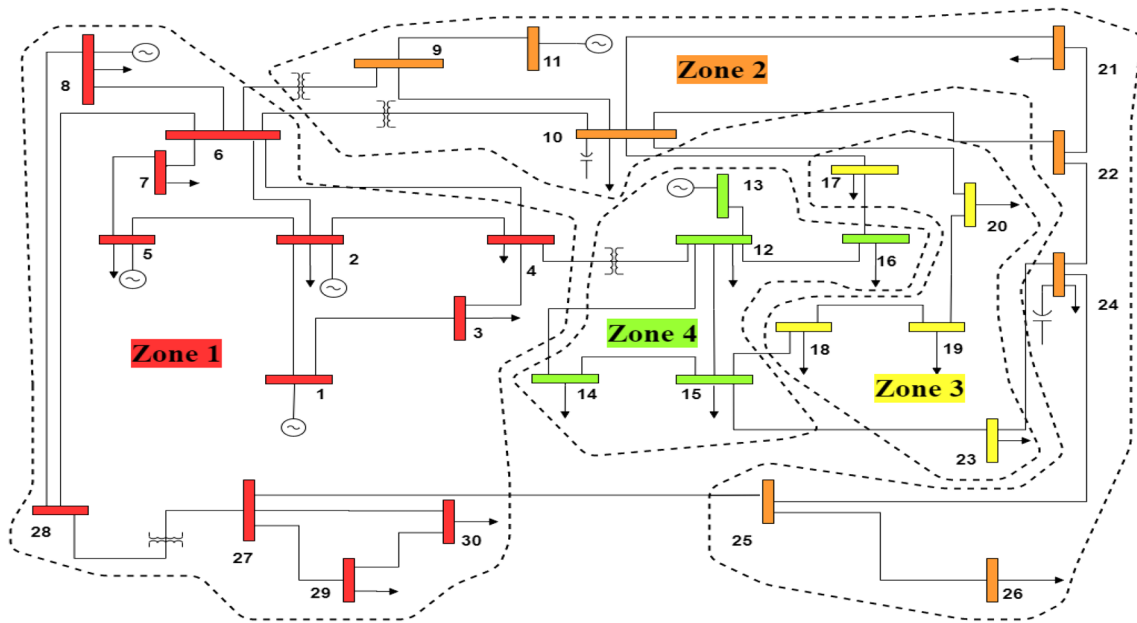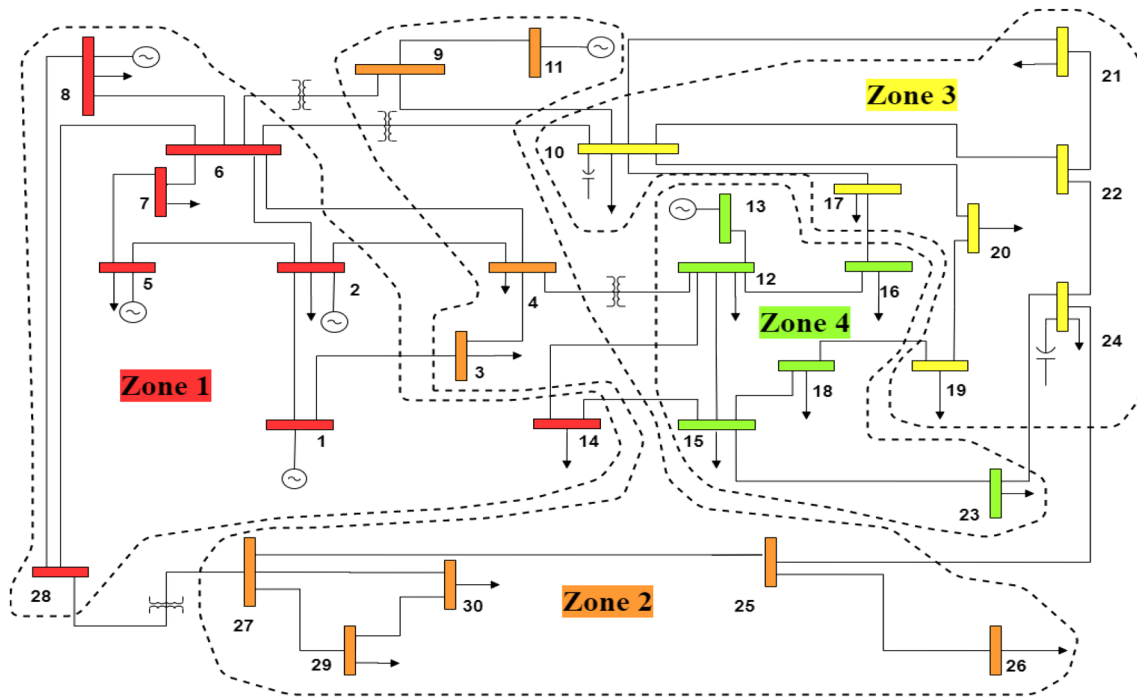
Fig. 1 Clusters/Zones for congested line 1–2

Fig. 2 Clusters/Zones for congested line 4–6

Table 3 Buses in combine clusters/zones

	Zone 1	Zone 2	Zone 3	Zone 4
Buses	1, 2, 5, 6, 7, **28**	3, 4, 9, 11, 25, 26, 27, 29, **30**	10, 17, 19, 20, 21, 22, 24	12, 13, 14, 15, 16, 18, 23
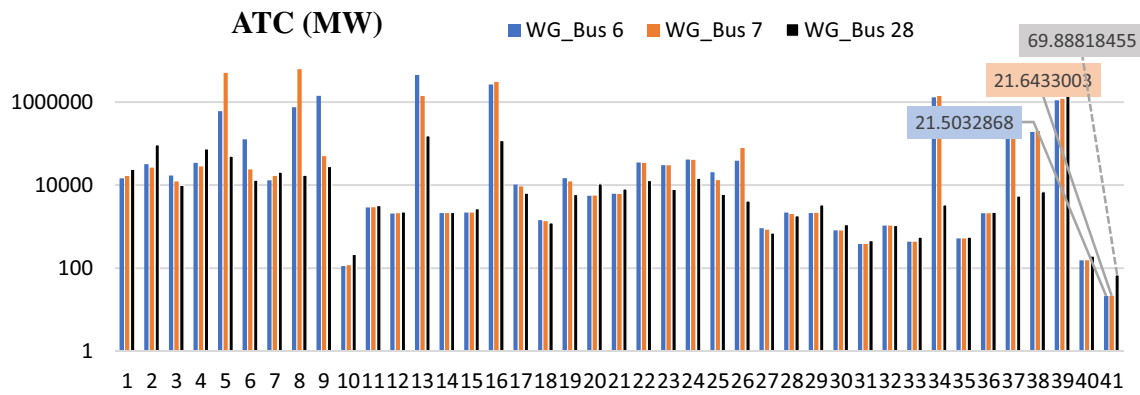
Fig. 3 ATC Comparison in limiting line between bus 6–28 due to optimally placed WG in Zone 1

transaction gives the line 6–28 as the limiting line of the system.

Zone 1 is selected as it is most sensitive for any transaction. WG at a different location is installed and the ATC value in the limiting is calculated which is shown in Fig. 3. The ATC value varies according to WG placed at different bus locations in a zone. Zone 1 has only bus 6, bus 7, and bus 28 at which there is no generating source. The WG has been integrated one by one on each bus of zone 1 and ATC corresponding to each bus has been calculated. It is found that bus 28 gives the maximum value of ATC. The ATC value is 69.89 MW which is higher among all the values as shown in Fig. 3. The only positive value of ATC is shown by the semi-log axis as the negative value will appear to zero in the figure. The maximum value of ATC is obtained when the WG is at bus 28. The proposed method also suggests the same bus by ATCDF calculation.

5.4 ATC calculation considering WG at different buses in zone 2

Let zone 1 has no option to installed WG or it is required multiple WG to installed in the system, then finding optimal bus in other zones is difficult. The ATCDF value helps to find the optimal bus location according to its values. The decreasing order can give many locations for WG integration. Here only one WG is considered for installation in zone 2.

The ATC is calculated by placing WG all the buses in zone 2. ATC value corresponding to all buses is shown in Fig. 4. Bus 30 shows the maximum value of ATC among all other values which was expected. According to the ATCDF value, the next location will be bus 29 for ATC enhancement which can also be validated from Fig. 5.
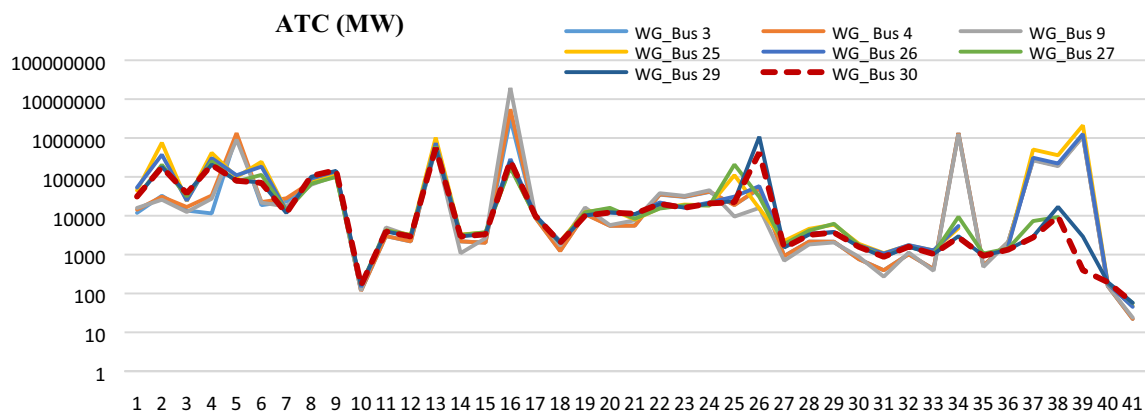

Fig. 4 ATC Comparison in limiting line between bus 6–28 due to optimally placed WG in Zone 2
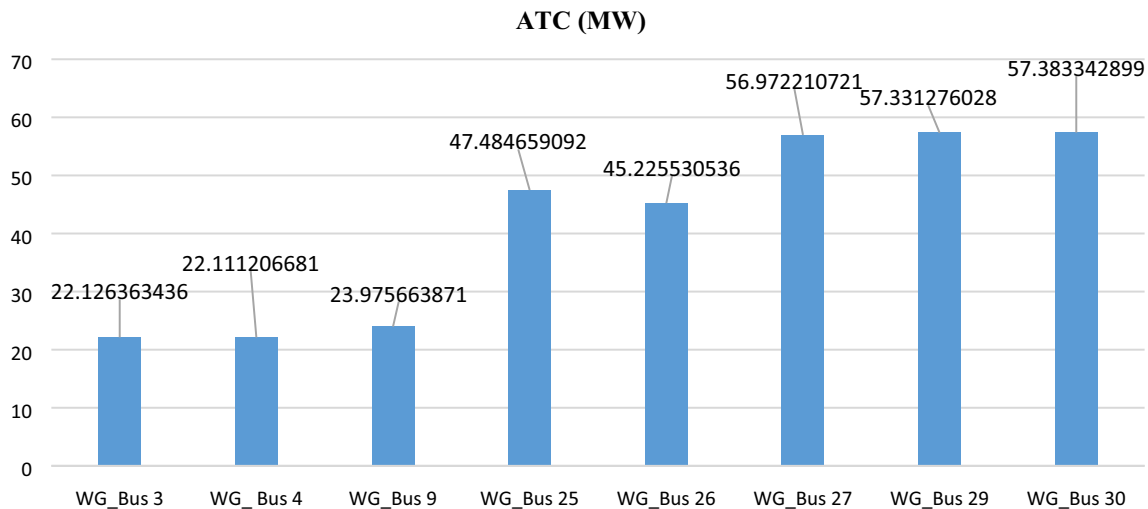
Fig. 5 ATC in limiting line due to WG at different bus location in Zone 2

6 Conclusion

The load is increasing day by day and to mitigate this renewable energy generation also increasing. The transmission line has its limit, it cants afford all the load demand. It requires system analysis during the transaction. ATC calculates the available power transfer capacity of the system. It is also useful in contingency analysis. This paper shows the optimal location of WG using proposed ATCDF values for ATC enhancement. The new approach has been considered for the optimal location of the WG. The comparison of ATC due to WG at different bus locations shows the optimally located WG according to ATCDF values enhance more ATC than others. The results also show the next optimal location of WG for maximum ATC enhancement. The ATCDF value helps in finding the optimal location in case of multiple WG integration or when it requires installing WG in different sensitive zones.

Declarations

Conflict of interest The authors declared that there is no conflict of interest.

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