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TCSC AND SVC OPTIMAL LOCATION TO IMPROVE THE PERFORMANCE OF POWER SYSTEM WITH WIND PENETRATION

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Abstract

Wind generation connection to power system affects steady state and transient stability. Furthermore, this effect increases with the increase of wind penetration in generation capacity. In this paper optimal location of FACTS devices is carried out to solve the steady state problems of wind penetration. Two case studies are carried out on modified IEEE39 bus system one with wind reduction to 20% and the second with wind penetration increase by 50% in the two cases system suffer from outage of one generator with load at bus 39 decreases from 1104 MW to 900 MW. The system suffers from min voltage reduction, total loss increases and violated of power and power angle limits. This paper found that series FACTS devices in certain range are the best type to solve these problems associated with wind penetration in power systems.

Keywords

Flexible AC transmission systems, genetic algorithms, optimization ,wind.

1. INTRODUCTION

Wind energy is gaining increasing importance throughout the world. This fast development of wind energy technology and of the market has large implications for a number of people and institutions: for instance, for scientists who research and teach future wind power, and electrical engineers at universities; for professionals at electric utilities who really need to understand the complexity of the positive and negative effects that wind energy can have on the power system; for wind turbine manufacturers; and for developers of wind energy projects, who also need that understanding in order to be able to develop feasible, modern and cost-effective wind energy projects [1].

All wind farms connected to grid shall endeavour to maintain the voltage wave form quality at the grid connection point, also to keep voltage and frequency deviation in its permissible value otherwise, the grid operator is authorized to disconnect the wind farm from the grid [2].
In this day and age, the world needs to look at the different natural energy sources available to us. Global warming could be due our energy craving lifestyle, so we should look into more environmentally friendly energy sources. But there are a range of advantages and disadvantages of wind energy to look at, including the many problems associated with wind turbines [3].

Advantages:

- Wind energy is friendly to the surrounding environment.
- Wind turbines take up less space than the average power station.
- Wind turbines are a great resource to generate energy in remote locations.

Disadvantages:

- The main disadvantage regarding wind power is down to the winds unreliability factor. In many areas, the winds strength is too low to support a wind turbine or wind farm.
- Wind turbine construction can be very expensive and costly to surrounding wildlife during the build process.
- The noise pollution from commercial wind turbines is sometimes similar to a small jet engine.

Wind turbine generators examples

- **SQUIRREL-CAGE INDUCTION GENERATORS**SCIGs are described as fixed-speed [4, 5].

- **DOUBLY-FED INDUCTION GENERATORS**The main advantage for this type is their ability to vary their operating speed in order to gain optimum power extraction from the wind [4, 6].

- **DIRECT-DRIVE SYNCHRONOUS GENERATORS**which is connected to the grid via a back-to-back voltage source converter [4, 7].

FACTS

A flexible AC transmission system (FACTS), in recent years, has become a well-known term for higher controllability in power systems by means of power electronic devices. Several FACTS devices have been introduced for various applications worldwide. The basic applications of FACTS devices are [8, 9]: power flow control, increase of transmission capability, voltage control, reactive power compensation, stability improvement and power quality improvement. However, because of the considerable cost of FACTS devices, it is important to minimize their number and obtain their optimal locations in the system.

- **Series Facts**

The TCSC is one of the series FACTS devices. It uses an extremely simple main circuit. In this FACTS device, a capacitor is inserted directly in series with the transmission line to be compensated, and a thyristor-controlled inductor is connected directly in parallel with the capacitor; thus, no interfacing equipment, like high voltage transformers are required. This makes the TCSC much more economic than other competing FACTS technologies [8, 10].

In [11], the TCSC may have one of the two possible characteristics - capacitive or inductive , respectively, to decrease or increase the overall reactance of line X_L. It is modeled with three ideal switched elements connected in parallel: a capacitor, an inductor, and a simple switch to short-circuit both of them when they are not needed in the circuit. The capacitor and the inductor are variable, and their values are dependent on the reactance and power transfer capability of the line in series with which the device is inserted. In order to avoid resonance, only one of the three elements can be switched at a time. Moreover, in order to avoid overcompensation of the line, the maximum value of the capacitance is fixed at $-0.8X_L$. For the inductance, the maximum is $0.2X_L$. The TCSC model presented in [11] is shown in Figure 1.

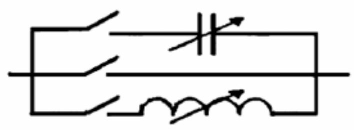

Figure 1 Model of the TCSC

In [12], the TCSC is a capacitive reactance compensator that consists of a series capacitor bank shunted by a TCR to provide smooth control of the series capacitive reactance. A model of the TCSC presented in [12] is shown in Figure 2. Another TCSC model was used in [13]. According to this model, a variable reactance is inserted in series with the line to be compensated, which is similar to the model used in [10]. This model, which is shown in Figure 3, is used in this work as the TCSC capacitive range, and the reactance is assumed to vary in the range from $-0.3X_L$ to $-0.7X_L$.

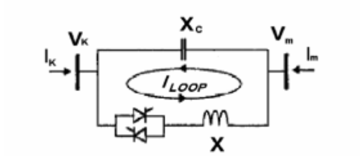

Figure 2 Model of the TCSC [12]

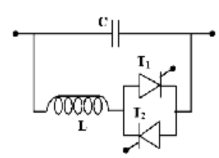

Figure 3 Model of TCSC [10]

- **Shunt devices [14]**

The most commonly used FACTS-device is the SVC or the version with voltage source converter called STATCOM. These shunt devices are operating as reactive power compensators. The main applications in transmission, distribution and industrial networks are:

- Reduction of unwanted reactive power flows and therefore reduced network losses.
- Keeping of contractual power exchanges with balanced reactive power.
- Compensation of consumers and improvement of power quality especially with huge demand fluctuations like industrial machines, metal melting plants railway or underground train systems.

- Compensation of thyristor converters e.g. in conventional HVDC lines.
- Improvement of static or transient stability.

The SVC may have two characters: inductive or capacitive. In the first case it absorbs reactive power while in the second one the reactive power is injected. The SVC is modeled with two ideal switched elements in parallel: a capacitance and an inductance as shown in Figure 4. It may take values characterized by the reactive power injected or absorbed at the voltage of 1 p.u. . The values are between -100 MVAr and 100 MVAr [14, 15].

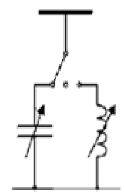

Figure 4 SVC model

This model is used in this paper for shunt device but with range from -1000 MVAr to 1000 MVAr

Below, main research areas regarding FACTS solutions for wind problems in power systems are reviewed [16].

A.Voltage stability

Reactive power consumptions of the connecting lines and loads may lead to a voltage collapse in a weak heavily loaded system. Such situations are quite typical for wind generation, which is often placed in remote areas and connected with long lines. If reactive power compensation provided by Wind Power Plants (WPP) is not sufficient, generated active power might need to be limited to avoid voltage instability [16, 17]. It is especially likely for a wind farm employing full scale converter turbines (FSWTs), which not only does not provide compensation but also consumes reactive power. Studies conducted in [16, 17] show that STATCOM applied at point of common coupling (PCC) of such plant greatly enhances system voltage stability, when connection to the main grid becomes weakened. Similar case was studied for DFIG based wind farm in [18].[19], [20] also analyze transient voltage stability enhancement of DFIG-WT based farms by a STATCOM. [20] Clearly shows proportional relation between STATCOM ratings and level of support. In [19] influence of STATCOM control strategy on post-fault voltage evolution was studied. Optimized neural network controller allows faster voltage restoration with smaller overshoot and oscillations. In [21] voltage stability of 486 MW DFIG based offshore wind farm is indirectly addressed through the compliance analysis with UK grid codes. Conclusion is made that for short connection (20km), DFIG can comply with grid codes without additional support. On the other hand, for 100km cable, STATCOM of at least 60MVAr would be needed to provide adequate voltage support from the wind farm. However, authors suggest that in both cases it could be beneficial, to cover whole reactive power demand by STATCOM, without relying on WTGs capabilities. Control is faster and less complicated in case of one centralized device, when compared to tens of turbines, distributed over a certain area. In such a light, more studies are needed, because in most of the publications usually WPP is modeled as one aggregated WTG (e.g. [16, 18, and 20]).

B. Frequency stability

To maintain frequency close to the nominal value, balance between generated and consumed power must be provided. When there is surplus of generated power, the synchronous generators (which are the core of the power system), tend to speed up. In result synchronous frequency rises. On the contrary, when there is not enough power generation to cover consumption, overloaded synchronous machines slow down and grid frequency drops. There has been done lot of research on adding energy storage for wind turbines to improve active power control (e.g. [16, 22] discuss provision of frequency support, load leveling and spinning reserve). However, here particular interest is when energy storage is incorporated in FACTS device. Such studies have been done in [23], for STATCOM with Battery Energy Storage System connected in parallel to regular DC-link capacitors. According to simulation results, 5MWh storage helps 50MVA SCIG based wind farm to track ½ hour active power set point, which was based on wind prediction. Therefore need for balancing power is reduced and wind power can be better dispatched. It is clear that energy storage would bring benefits in terms of frequency control and inertia emulation. Still, primary STATCOM control functions are maintained.

C. Power oscillations

In [19] it is shown that additional control loop for STATCOM controller can help to damp power oscillations, while basic voltage support function is maintained. In [19] also optimized neural network controller attenuates local plant oscillations of DFIG based wind farm, during post fault period. Wind farms have not been considered yet in literature, to play specific role in the intra-area or inter-area oscillations. On other hand FACTS devices are widely recognized as one so such studies could be performed [16].

D. Power quality

In [24] is shown, that dynamic reactive power compensation device like STATCOM can solve this problem. Very interesting issue is studied in [25]. Capacitances of low loss cables that are used in wind farms together with main transformers inductance form poorly damped resonant tank, with resonance frequency between 11^{th} and 35th harmonic. By proper controller gain selection it can be ensured that real part of STATCOM complex impedance is negative for all signals in desired frequency spectrum. What means that STATCOM would absorb active power carried by harmonics and re-inject active power at fundamental frequency [16, 25].

This paper focuses on solving the steady state problems of wind penetration (such as total loss increase and the need of generation reserve to cover wind variation) by using FACTS devices. The main objective here is to reduce the total loss of the system by using FACTS which will give a cover for wind generation variation. The wind generator is considered as a generator produces active power and consumes reactive power.

2. PROPOSED OPTIMIZATION TECHNIQUE

The problem is to find the optimum numbers, locations and reactances of the TCSCs to be used in the power system. This problem is a nonlinear multi-objective one. The GA method will be used in this paper where it only uses the values of the objective function and less likely to get trapped at a local optimum. The selected method is to use two genetic algorithms with number of generations of 30, fitness limit of zero and the other parameters are taken as the default values in MATLAB (e.g. population size = 20). The first one is to find the location and number of FACTS devices by computing the minimum total loss after inserting FACTS devices in the system. After location and number of the devices are obtained they have been given to another genetic algorithm to obtain the best rating of them by also computing the total loss. Details of program are as follows [26]:

- The program starts with a group of random population for the location in binary, Then this random population is multiplied by the values of TCSCs in a specified range And the result of the multiplication will change in the reactance of the system (in case of shunt this random population is multiplied by the values of SVCs in a specified range and the result of the multiplication will change in the charging susceptance of each bus.
- After that power flow is carried out for the system with TCSC or SVC all over the range.
- Then, the total loss is calculated and fitness function is computed.
- Finally stopping criteria is checked if it is not reached, another generation will start by reproduction, crossover and mutation.

Details of program are shown in figure 5.

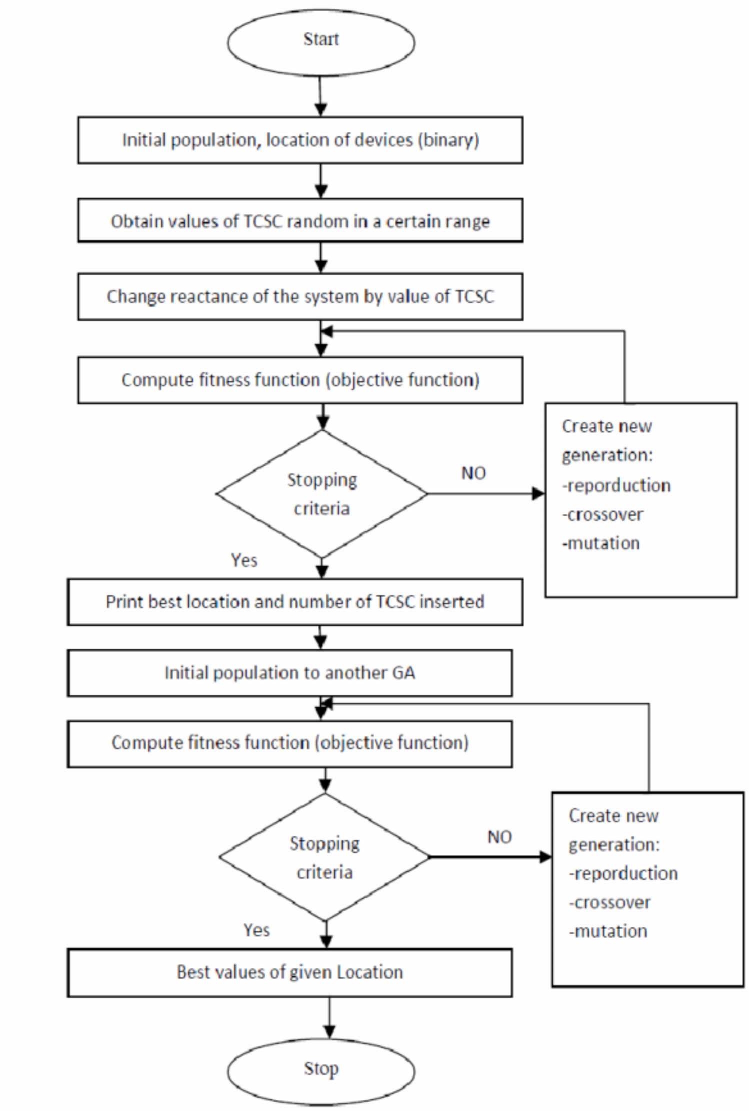

Figure 5 Flow chart of the proposed optimization technique

The objective is to minimize the total losses

Total system losses = Sum of real loss of all system lines

Calculation of total loss is obtained by using MATLAB m-files in MATPOWER [27] to calculate the power flow of the system and compute the sum of real losses.

In this paper the reactance of each branch in MATPOWER case is replaced by variable reactance function of the value of TCSC reactance added as in equation (2) in case of series FACTS.

New reactance = Old reactance + X TCSC (2)

In case of shunt FACTS the charging susceptance of each bus in MATPOWER case is replaced by variable reactance function of the value of SVC added.

The program in [26] has been improved to make GA search for only the locations in the most sever three lines and the lines around them in case of series and search for the most sever 9 buses in case of shunt.

Ranking of lines:

Ranking is made according to the following technique:

1. Make outage of system lines one by one
2. Check min voltage of the system after each outage
3. The line which its outage cause lower min voltage than the others cause will have the higher ranking.
4. Genetic algorithm is search in the higher three lines or any number according to case and the lines surrounding them without considering transformers lines.
5.

For shunt devices ranking as follows:

1. The buses are arranged according to the magnitude of its active power
2. The bus with higher active power has higher ranking
3. Then genetic algorithm search in a number of first buses in ranking equal to the number of location available in series case.

- For the IEEE 39 bus system under case study 1 conditions (outage of generator at bus 39 and wind reduction by 20% with load at bus 39 decreases from 1104 MW to 900 MW) the lines and buses for FACTS are as following:

Lines for series FACTS case study1:lines connected buses (1-39), (20-34), (5-8), (10-32) and lines surrounding them.

Buses for shunt FACTS case study1: Buses (4, 34, 8, 36, 31, 33, 32, 35, 20 and 37)

- For the IEEE 39 bus system under case study 2 conditions (outage of generator at bus 39 and wind increase by 50% with load at bus 39 decreases from 1104 MW to 900 MW) the lines and buses for FACTS are as following:

Lines for series FACTS case study2:lines connected buses (8-9), (3-4), (6-31) and lines surrounding them.

Buses for shunt FACTS case study2: Buses (4, 34, 8, 36, 31, 33, 32, 35, 20, 37, 38 and 39)

3. CASE STUDY

- **Case study 1**

The modified IEEE 39-bus system is taken as the system under study. A one line diagram of the system is shown in Figure 6. The data of the system is given in [27]. The system consists of 39 buses, 46 branches and 10 generators at buses 30, 31,32,33,34, 35, 36, 37, 38 and 39. The case under study is an outage of the generator at bus 39 and reduction of wind generator at bus 37 by 20% with load at bus 39 decreases from 1104 MW to 900 MW .This study is carried out for range of TCSC from -30% to -70% of the line reactance and SVC with range -1000 MVAr to 1000 MVAr.

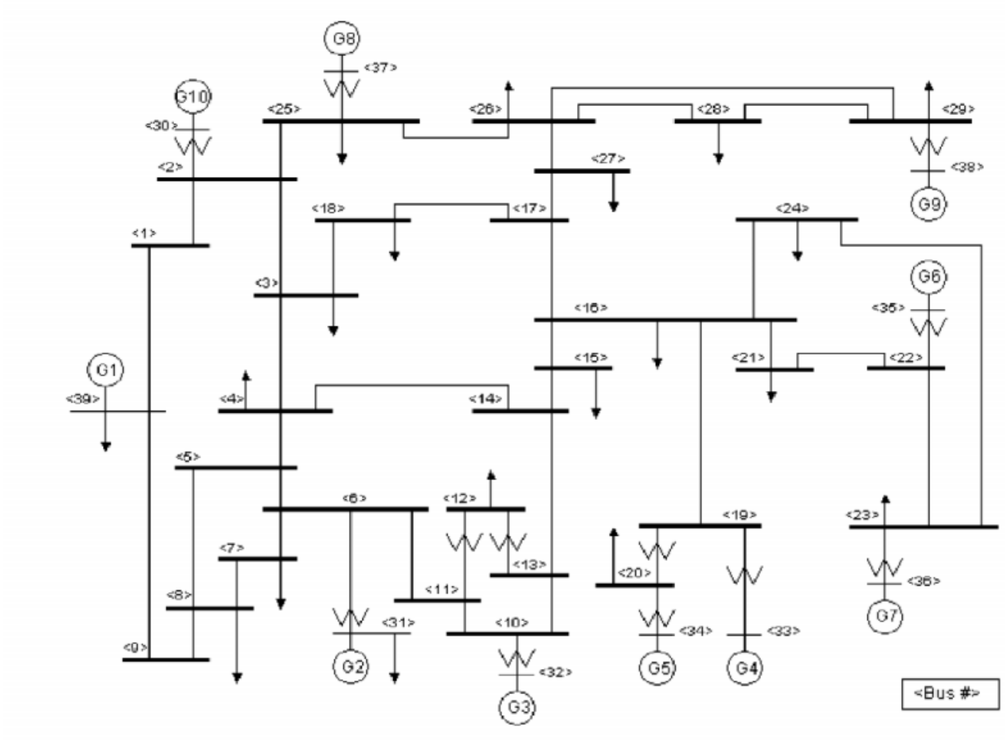

Figure 6 IEEE 39 bus system [28]

4. Simulation Results:

Results show that:

- **Without FACTS :** line 37 power are out of limit given in [29](100.55%)

- **With series FACTS capacitive range (-0.7 to -0.3 X_{line}) :** succeed to return line 37 power to inside its limits which given in [29] (99.687%)

- **With shunt FACTS :** failed to return line 37 to its limit(100.487 %)

Table 1 Voltage profile with and without FACTS

bus number	V without FACTS	V with FACTS C range	V with shunt FACTS
1	0.8647	0.9839	0.87
7	0.883	0.9444	0.8853
8	0.8745	0.9421	0.8769
9	0.8172	0.939	0.8229
39	0.7937	0.9368	0.801

As shown in Table 1:

- **Without FACTS:** the grey markers buses suffer from voltage reduction than 0.9 PU which indicate bad voltage profile**.**
- **With series FACTS capacitive range (-0.7 to -0.3 X_{line}):**no buses suffer from voltage reduction which improvement to voltage profile.
- **With shunt FACTS :**the grey markers buses suffer from voltage reduction than 0.9 PU which indicate bad voltage profile.

Table 2 power angle (delta) with and without FACTS

bus number	Power angel without FACTS	Power angel with FACTS C range	Power angel with shunt FACTS
1	-47.1266	-32.2858	-46.9185
2	-35.3893	-29.8945	-35.2691
3	-35.5177	-30.3834	-35.4013
4	-32.3685	-27.8129	-32.2689
7	-31.2055	-29.634	-31.1153
8	-32.7235	-30.1213	-32.6267
9	-46.1495	-33.8841	-45.9436
13	-26.8954	-23.6451	-26.8143
14	-29.9936	-26.0089	-29.9007
15	-32.6721	-28.0904	-32.5645
16	-32.086	-27.3236	-31.9758
17	-33.8988	-28.9436	-33.7839
18	-34.9712	-29.9356	-34.855
21	-29.5958	-24.8723	-29.4879
24	-31.967	-27.2043	-31.8568
25	-34.5357	-28.9303	-34.404
26	-33.9538	-28.6585	-33.8297
27	-35.1527	-29.9831	-35.031
28	-30.3676	-25.1052	-30.2456
30	-32.8586	-27.4116	-32.7415
37	-28.9861	-23.4317	-28.8578
39	-56.2736	-36.4061	-55.9182

From Table 2.

- Without FACTS and with shunt FACTS system suffer from unacceptable power angle value as shown in grey markers
- Series FACTS has better power angel range than without FACTS and shunt.
- Also series FACTS succeed to decrease power angel at wind bus.

FACTS numbers and rating:

Table 3 FACTS value capacitive range case1

Line number	From bus	To bus	Lines reactance	FACTS capacitive Range reactance value % of line reactance
1	1	2	0.0411	-70
2	1	39	0.025	-30
7	4	5	0.0128	-70
13	7	8	0.0046	-70
14	8	9	0.0363	-70
15	9	39	0.025	-70
17	10	13	0.0043	-70

Table 4 shunt FACTS value

Bus No.	shunt FACTS injected (pu)	shunt FACTS injected (MVAr)
20	10	1000
31	2.3245	232.45
32	-4.0035	-400.35
35	-3.2942	-329.42
39	10	1000

Summary

Table 5 summary

	Without FACTS	With FACTS C range	With shunt FACTS
Total loss % of load	**1.4**	**1.177**	**1.3786**
Vmax (pu)	**1.064**	**1.064**	**1.063**
Vmin (pu)	**0.794**	**0.937**	**.801**
Power angel max (degree)	**0**	**0**	**0**
Power angel min (degree)	**-56.27**	**-36.41**	**-55.92**
Wind line power loss (MW)	**1.157**	**1.092**	**1.152**

From Table 5 it is clear that:

- **Without FACTS system** suffer from low min voltage (0.794 pu), high total losses and high power angle value (-56.27).

- **With series FACTS capacitive range (-0.7 to -0.3 X_{line})** with adding only 7 devicesmin. voltage increase to 0.937 which improvement for voltage profile and losses minimized to 1.177% which will give wind more spare to its variation with max voltage kept at 1.064 pu .Also the power loss of line connected to wind generator reduced to 94.4% which give also more spare for wind variation **.**it can be found that power angle also reduced to -36.41.

- **With shunt FACTS :** with adding 5 devicesmin voltage increase to only 0.801 and losses decreases to 1.3786% which will give wind more spare to its variation with max voltage kept at 1.063 pu . Also the power loss of line connected to wind generator reduced to 99.57% which give sparer also for windvariation.

- **Case study 2**

The modified IEEE 39-bus system is taken as the system under study. A one line diagram of the system is shown in Figure 6. The data of the system is given in [27]. The system consists of 39 buses, 46 branches and 10 generators at buses 30, 31, 32, 33, 34, 35, 36, 37, 38 and 39. The case under study is an outage of the generator at bus 39 and increasing of wind generator at bus 37 by 50% with load at bus 39 decreases from 1104 MW to 900 MW . This study is carried out for range of TCSC from -30% to -70% of the line reactance and SVC with range -1000 MVAr to 1000 MVAr.

Simulation Results:

Results show that no line suffers from power out of limit.

Table 6 Voltage profile with and without FACTS case2

bus number	V without FACTS	V with FACTS C range	V with shunt FACTS
1	0.8775	0.9559	0.8823
9	0.852	0.9247	0.8569
39	0.8203	0.9138	0.8269

As shown in Table 6:

- **Without FACTS:**the grey markers buses suffer from voltage reduction than 0.9 PU which indicate bad voltage profile.
- **With series FACTS capacitive range (-0.7 to -0.3 X_{line}) :**no buses suffer from voltage reduction which improvement to voltage profile.

- **With shunt FACTS :**the grey markers buses suffer from voltage reduction than 0.9 PU which indicate bad voltage profile.

Table 7 power angle (delta) with and without FACTS case2

bus number	Power angel without FACTS	Power angel with FACTS C range	Power angel with shunt FACTS
1	-33.9394	-24.8264	-33.8139
9	-35.3638	-27.5765	-35.2232
37	-7.9869	-3.9295	-7.9324
39	-43.6912	-30.3794	-43.4381

From Table 7.

- **Without FACTS:**system suffer from high values of power angle (delta)

- **Series FACTS :** succeed to reduce the power angles to acceptable values but**Shunt FACTS** failed in that.

FACTS numbers and rating:

Table 8 FACTS value capacitive range case2

Line number	From bus	To bus	Lines reactance	FACTS capacitive Range reactance value % of line reactance
8	4	14	0.0129	-70
9	5	6	0.0026	-70
11	6	7	0.0092	-34
12	6	11	0.0082	-70
13	7	8	0.0046	-30
14	8	9	0.0363	-63.13
15	9	39	0.025	-70

Table 9 shunt FACTS value

Bus No.	shunt FACTS injected (pu)	shunt FACTS injected (MVAr)
20	10	1000
32	7.8059	780.59
33	-1.435	-143.5
34	-0.9771	-97.71
39	10	1000

Summary

Table 10 summary

	Without FACTS	With FACTS C range	With shunt FACTS
Total loss % of load	**1.516**	**1.39**	**1.505**
Vmax (pu)	**1.064**	**1.063**	**1.064**
Vmin (pu)	**0.82**	**0.914**	**0.827**
Power angel max (degree)	**0**	**0**	**0**
Power angel min (degree)	**-43.69**	**-30.38**	**-43.44**
Wind line power loss (MW)	**3.836**	**3.771**	**3.831**

From Table 10 it is clear that:

- **Without FACTS system** suffer from low min voltage (0.82 pu), high total losses and bad power angle values.
- **With series FACTS capacitive range (-0.7 to -0.3 X_{line})** with adding only 7 devicesmin voltage increase to 0.914 and losses minimized to 1.39 % which will give wind more spare to its variation with max voltage kept at 1.063 pu. Also the power loss

of line connected to wind generator reduced to 98.3 % which give sparer also for wind variation**.** It can be found that power angle value reduced to -30.38.

- **With shunt FACTS :** with adding 5 devicesmin voltage increase to only 0.827 which indicates bad voltage profile and losses decreases to 1.505 % which will give wind more spare to its variation with max voltage kept at 1.064 pu . Also the power loss of line connected to wind generator reduced to 99.87 % which give sparer also for windvariation. It can be found that power angle value reduced to -43.44 only.

Conclusion

In this paper, optimal location of FACTS devices is carried out by using genetic algorithm to cover the problem associated with wind penetration in power systems. The method in this paper is exanimate in a modified IEEE 39 bus system. Two case studies are carried out one for wind power decrease and the other with wind power increase respectively with the highest generator out and load at bus 39 decreases from 1104 MW to 900 MW in the two cases. Results show that: series FACTS with capacitive range is the best solution for this problem where it can keep the system operate without power, voltage and power angel limits violated also reduce the total loss of the system which gives wind more spare to cover its generation variation, also it increase the min voltage to acceptable limit which is improvement in voltage profile.

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