Reactive Power Control to Assist Wind Penetration without Effect on System Operation

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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 using Genetic Algorithm (GA). Cases studied are carried out on modified IEEE39 bus system with wind penetration around 7% of system generation with change in reactive power injection to wind bus from the network. In all cases the system suffers from outage of one generator with load in one of system buses decrease by 15%. The system suffers from minimum voltage reduction, total loss increases and violation of power angle limits. Results prove that series FACTS devices in certain range are able to solve these problems associated with wind penetration in power systems.

Keywords: FACTS, TCSC, genetic algorithm, optimization, wind penetration

I. INTRODUCTION

Nowadays, the world needs to look at the different available natural energy sources. So it is necessary to look into more environmentally friendly energy sources as wind energy. But there are a range of advantages and disadvantages of wind energy to look at, for examples wind energy is friendly to the surrounding environment. Also wind turbines take up less space than the average power station and are considered as great resources to generate energy in remote locations. But the main disadvantage regarding wind power is down to the winds unreliability factor. Also wind turbine construction can be very expensive and the noise pollution from commercial wind turbines should be considered [1]. Moreover, all wind farms connected to grid shall endeavor to maintain the voltage wave form quality at the grid connection point, also to keep voltage and frequency deviation in their permissible value otherwise, the grid operator is authorized to disconnect the wind farm from the grid [2].

A flexible AC transmission system (FACTS) has higher controllability in power systems by means of power electronic devices. The basic applications of FACTS devices are power flow control, increase of transmission capability, voltage control, reactive power compensation, stability improvement and power quality improvement [3, 4]. However, because of the considerable cost of FACTS devices, it is important to minimize their number and obtain their optimal locations in the system.

The Thyristor-Controlled Series Compensation (TCSC) is one of the series FACTS devices. In this 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. The TCSC is more economic than other competing FACTS technologies [3, 5].

In [6], the TCSC may have one of the two possible characteristics—capacitive or inductive, respectively, to decrease or increase the overall reactance of line XL. In order to avoid overcompensation of the line, the maximum value of the capacitance is fixed at -0.8XL. For the inductance, the maximum is 0.2XL.

Another TCSC model was used in [7]. 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 [5] as shown in Figure 1. This model is used in this work as the TCSC range, and the reactance is assumed to vary in the range from -0.3XL to -0.7XL which is better range to deal with wind problems [8].

Figure 1 - Model of TCSC [5]

Main research areas regarding FACTS solutions for wind problems in power systems are reviewed. The problems associated with wind in power system are voltage stability, frequency stability, power oscillations and power quality and the FACTS are recommended to solve these problems [9].
According to [9], voltage stability should be monitoring with wind penetration where 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.

Also if reactive power compensation provided by the WPP (wind power plant) is not sufficient, generated active power might need to be limited to avoid voltage instability [10]. Studies conducted in [10] show that STATCOM applied at PCC (point of common coupling) of such plant greatly enhances system voltage stability.

Similar case was studied for DFIG based wind farm in [11]. Due to crowbar protection, WPP reactive power support is limited. In result, without a STATCOM voltage cannot be restored when one of the connecting lines was disconnected due to fault.

Authors of [12, 13] also analyze transient voltage stability enhancement of DFIG-WT based farms by a STATCOM. Reference [13] clearly shows proportional relation between STATCOM ratings and level of support. In [12], 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 [14], voltage stability of 486MW 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.

Reference [9] finds that frequency stability is an important parameter with wind penetration where active power control requirement stated in the grid codes is related to 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 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. reference [15] discusses 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 [16], for STATCOM with Battery Energy Storage System connected in parallel to regular DC-link capacitors. According to simulation results, 5 MWh 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.

Power oscillation damping is one of the existing problems in power systems. In [12], it is shown that additional control loop for STATCOM controller can help to damp power oscillations, while basic voltage support function is maintained.

Another research area is wind power quality improvement with FACTS devices. It is especially attractive in case of Wind generator connected to a weak grid, where changing wind speed causes voltage fluctuations at wind farm PCC and flicker. In [17], it is shown that dynamic reactive power compensation device like STATCOM can solve this problem.

Very interesting issue is studied in [18]. 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 11th 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. This means that STATCOM would absorb active power carried by harmonics and re-inject active power at fundamental frequency [18].

In [19], Instead of shunt compensation DVR was used. This device, by exchanging active power with the grid, injects series voltage between PCC and wind farm terminals to cover voltage reduction caused by grid fault. In such a way fault is not seen from the wind turbine point of view.

In [20], a 28 bus test system is considered where the wind penetration varies from 10% to 99% over the day. This causes a large variation at different bus voltages violating the grid code. A shunt FACTS device (SVC) is used to mitigate this problem at the buses connected to wind generators. Thereafter, suitable locations for the SVC placement are identified to enhance the voltage stability and reduce system power loss.

In [21], study considered the problem of transient stability in networks with wind power. The effects of large and sudden wind changes are considered and their impact on system stability is analyzed. Reference [21] found that FACTS devices are capable of improving transient stability of the system. Also if the control logic is implemented in a manner in which FACTS accumulate energy of disturbance then the critical clearing time of the system can be increased and the time during which the generators stay synchronized is longer. The size of
FACTS determines how much energy FACTS can accumulate.

In [22], the UPQC is utilized to enhance the low-voltage ride-through (LVRT) capability of the doubly fed induction generator (DFIG)-based wind energy conversion system (WECS) according to the grid connection requirement. UPQC is applied to protect the system from ground faults, allows fast restoring of generation system steady state characteristics, improves the system power factor, and prevent the system from rotor over-current and dc-link overvoltage. A comparison between the LVRT results using the UPQC and the results when using STATCOM or DVR is also presented.

This paper focuses on solving the steady state problems of wind penetration in power system (such as total loss increase and the need of reactive power to wind generation) by using FACTS devices. The main objective is to reduce the total loss of the system by using FACTS which will cover the wind generation penetration effects. The wind generator is considered as a generator produces active power and consumes reactive power. Four cases of wind penetration are studied, wind generation with reactive power injected to the wind bus from the network is 10%, 20%, 30% and 40% respectively.

II. Proposed Optimization Technique

The problem is to find the optimum numbers, locations and reactances of the FACTS 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 system. After location and number of the devices are obtained they have been given to another genetic system.

1. 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.
2. After that power flow is carried out for the system with TCSC all over the range.
3. Then, the total loss is calculated and fitness function is computed.
4. Finally stopping criteria is checked if it is not reached, another generation will start by reproduction, crossover and mutation.
5. 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 [23] to calculate the power flow of the system and compute the sum of real losses.

The reactance of each branch 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

In this paper the program in [23] has been improved to make GA search for only the locations in the most severe lines and the lines around them.

Ranking of lines:
Ranking of lines is made according to the following technique:
1. Make outage of system lines one by one.
2. Check minimum voltage of the system after each outage.
3. The line which its outage causes lower minimum voltage than the others cause, will have the higher ranking.
4. Genetic algorithm searches in the higher three ranked lines or any number according to the case and the lines surrounding them without considering transformers lines.

For the IEEE 39 bus system under cases studied conditions, the lines recommend for series FACTS insertion are as follows:
Lines connected buses (1-2), (5-8), (9-39) and lines surrounding them.

III. Case study

The modified IEEE 39-bus system is taken as the system under study. A one line diagram of the system is shown in Figure 2. The data of the system is given in [24]. 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 cases under study are an outage of the generator at bus 39 and increasing of reactive power injected from the network to wind generator at bus 37 by 10%, 20%, 30% and 40% with load at bus 39 decreases from 1104 MW to 900 MW. These studies are carried out for range of TCSC from -30% to -70% of the line reactance.
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Figure 2 IEEE 39 bus system [25]

Simulation Results:

Simulation results show that no line suffers from active power out of limits given in [26]. Table 1 shows the system parameters profile with reactive power injected from the network to wind bus is 10% of wind generation.

Table 1 - System parameters profile with reactive power injected from the network to wind bus is 10% of wind generation

<table>
<thead>
<tr>
<th>Without FACTS</th>
<th>With FACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss % of load</td>
<td>1.457</td>
</tr>
<tr>
<td>Vmax (pu)</td>
<td>1.063</td>
</tr>
<tr>
<td>Vmin (pu)</td>
<td>0.771</td>
</tr>
<tr>
<td>Power angle max (degree)</td>
<td>0</td>
</tr>
<tr>
<td>Power angle min (degree)</td>
<td>-54.32</td>
</tr>
<tr>
<td>Q at wind bus (MVAr)</td>
<td>-54</td>
</tr>
</tbody>
</table>

As shown in Table 1, with reactive power injected to wind bus is 54 MVAr (10% of wind generation) it can be found that:

- **Without FACTS** system suffers from low minimum voltage (0.771 p.u.), high total losses and high power angle value (-54.32).
- **With series FACTS in range (-0.7 to -0.3 Xline)** with adding only 5 devices the minimum voltage increases to 0.937 p.u. which is considered as an improvement in voltage profile and losses are minimized to 1.22% which will give wind power additional spare to its variation with maximum voltage kept at 1.064 p.u. It can be found that power angle is also reduced to -33.99°.

Table 2 shows the system parameters profile with reactive power injected from the network to wind bus is 20% of wind generation.

Table 2 - System parameters profile with reactive power injected from the network to wind bus is 20% of wind generation

<table>
<thead>
<tr>
<th>Without FACTS</th>
<th>With FACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss % of load</td>
<td>1.505</td>
</tr>
<tr>
<td>Vmax (pu)</td>
<td>1.063</td>
</tr>
<tr>
<td>Vmin (pu)</td>
<td>0.756</td>
</tr>
<tr>
<td>Power angle max (degree)</td>
<td>0</td>
</tr>
<tr>
<td>Power angle min (degree)</td>
<td>-55.29</td>
</tr>
<tr>
<td>Q at wind bus (MVAr)</td>
<td>-108</td>
</tr>
</tbody>
</table>

As shown in Table 2, with reactive power injected to wind bus is 108 MVAr (20% of wind generation) it can be found that:

- **Without FACTS** system suffers from low minimum voltage (0.756 p.u.), high total losses and high power angle value (-55.29).
- **With series FACTS in range (-0.7 to -0.3 Xline)** with adding only 7 devices the minimum voltage increases to 0.932 p.u. which is considered as an improvement in voltage profile and losses are minimized to 1.248 % which will give wind power additional spare to its variation with maximum voltage kept at 1.064 p.u. . It can be found that power angle is also reduced to -34.27°.

Table 3 shows the system parameters profile with reactive power injected from the network to wind bus is 30% of wind generation.
As shown in Table 3, with reactive power injected to wind bus is 162 MVAr (30% of wind generation) it can be found that:

- **Without FACTS** system suffers from low minimum voltage (0.738 p.u.), high total losses and high power angle value (-56.55).
- **With series FACTS in range (-0.7 to -0.3 X_{lin})** with adding only 5 devices the minimum voltage increases to 0.902 p.u. which is considered as an improvement in voltage profile and losses are minimized to 1.27% which will give wind power additional spare to its variation with maximum voltage kept at 1.063 p.u.. It can be found that power angle is also reduced to -33.38°.

Table 4 shows the system parameters profile with reactive power injected to wind bus is 40% of wind generation.

As shown in Table 4, with reactive power injected to wind bus is 216 MVAr (40% of wind generation) it can be found that:

- **Without FACTS** system suffers from low minimum voltage (0.713 p.u.), high total losses and high power angle value (-58.37).
- **With series FACTS in range (-0.7 to -0.3 X_{lin})** with adding only 5 devices the minimum voltage increases to 0.902 p.u. which is considered as an improvement in voltage profile and losses are minimized to 1.44% which will give wind power additional spare to its variation with maximum voltage kept at 1.063 p.u.. It can be found that power angle is also reduced to -41.69°.

Table 5 shows the FACTS values and location in the cases studied.

### Table 3 - System parameters profile with reactive power injected from the network to wind bus is 30% of wind generation

<table>
<thead>
<tr>
<th></th>
<th>Without FACTS</th>
<th>With FACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss % of load</td>
<td>1.57</td>
<td>1.27</td>
</tr>
<tr>
<td>Vmax (pu)</td>
<td>1.064</td>
<td>1.063</td>
</tr>
<tr>
<td>Vmin (pu)</td>
<td>0.738</td>
<td>0.928</td>
</tr>
<tr>
<td>Power angle max (degree)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Power angle min (degree)</td>
<td>-58.37</td>
<td>-41.69</td>
</tr>
<tr>
<td>Q at wind bus (MVAr)</td>
<td>-162</td>
<td>-129</td>
</tr>
</tbody>
</table>

### Table 4 - System parameters profile with reactive power injected from the network to wind bus is 40% of wind generation.

<table>
<thead>
<tr>
<th></th>
<th>Without FACTS</th>
<th>With FACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loss % of load</td>
<td>1.67</td>
<td>1.44</td>
</tr>
<tr>
<td>Vmax (pu)</td>
<td>1.063</td>
<td>1.063</td>
</tr>
<tr>
<td>Vmin (pu)</td>
<td>0.713</td>
<td>0.902</td>
</tr>
<tr>
<td>Power angle max (degree)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Power angle min (degree)</td>
<td>-58.37</td>
<td>-41.69</td>
</tr>
<tr>
<td>Q at wind bus (MVAr)</td>
<td>-216</td>
<td>-206</td>
</tr>
</tbody>
</table>

### IV. 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. Cases studied are carried out on modified IEEE39 bus system with wind penetration around 7% of system generation with change in reactive power injection to wind bus from the network. In all cases the system suffers from outage of one generator with load in one of system buses decrease by 15%. Results show that
series FACTS with capacitive range is the best solution for this problem where it can keep the system operates without power, voltage and power angel limits violated. Also the total power loss of the system is reduced which gives wind additional spare to cover its generation variation. Also it increases the minimum voltage to acceptable limit which is considered as an improvement in voltage profile.

References

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