Ain Shams University, Faculty of Engineering,

Electrical Power and Machines Department

Application of FACTS to Enhance the Performance of Power System with Growing Wind Power Penetration

By

Mahmoud Abdallah Attia

M. Sc. Electrical Engineering, Ain Shams University, 2010

A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Doctor of Philosophy in Electrical Engineering

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List of Abbreviations

- AI : Artificial intelligence
- BSA : Bacterial swarming algorithm
- FACTS : Flexible AC transmission systems
- GA : Genetic algorithm
- HVDC : High voltage direct current
- IP : Interior point
- LP : Linear programming
- Max : Maximum
- Min : Minimum
- NLP : Nonlinear programming
- NR : Newton Raphson
- OPF : Optimal power flow
- PSO : Partical swarm optimization
- QP : Quadratic programming
- STATCOM : Static Synchronous compensator
- SVC : Static VAr compensator
- TCPST : Thyristor controlled phase shifting transformer
- TCVR : Thyristor controlled voltage regulator
- TCSC : Thyristor-controlled series compensators
- TTC : Total transfer capability
- UPFC : Unified power flow controller
- WTG : Wind turbine generator
- CSWTG : Constant speed wind turbine generator
- SCIG : Squirrel cage induction generator
- PCC : Point of common coupling
- DFIG : double fed induction generator
- LVRT : Low voltage ride through
- WPP : Wind power plant
- TCR : Thyristor Controlled Reactor
- TSR : Thyristor Switched Reactor
- TSC : Thyristor Switched Capacitor
- C range : Capacitive range
- L-C range : Inductive-capacitive range
- DVR : dynamic voltage restorer
- TSO : Transmission System Operators
- WRIG : Wound rotor induction generator
- PMSG : Permanent magnet synchronous generator
- WRSG : Wound rotor synchronous generator

List of Symbols

- θ_p : Phase shift angle
- Delta (δ) : Power angle
- P : Power flow
- P_d : Power demand
- P_g : Generated power
- P_{loss} : Power loss
- % : A percent
- Q : Reactive power flow
- Q_d : Reactive power demand
- Q_g : Generated reactive power
- Q_{loss} : Reactive power loss
- Q_s : Reactive power injected or absorbed by SVC
- S : Complex power
- T_v : Tab change transformer turns ratio
- V : Voltage
- X_{TCSC} : Reactance added to line by TCSC
- X_l : Line reactance
- α : Firing angle of thyristor

Abstract

Wind generation connection to a power system affects its steady state and transient stability. This effect increases with the increase of wind generation capacity penetration. Most of literature don't cover the steady-state performance of the power system after wind variation even with the bad effects of this variation on voltage profile, power angle and power limits. Furthermore, the literature is mainly concerned with the shunt FACTS devices for example STATCOM and SVC to enhance the performance of the power system suffering from wind penetration, and minor interest is directed to series FACTS as TCSC. There may give better techno-economical solutions for the problems associated with wind penetration in power system than shunt devices.

Some publications are concerned with SVC as a way to enhance the power system performance with wind penetration. SVC can't perform well with low voltage at its location as proved in this thesis. Also the literature did not cover the wind penetration limit while keeping the power system operated without any violation in its indices. Finally, some literatures consider the cost of FACTS devices as an additional problem of wind energy penetration, although the FACTS may eventually make net saving in the cost through reducing the total loss.

In this work, determining the optimal location of FACTS devices to solve the problem associated with wind penetration in power systems is carried out by using genetic algorithm optimization technique. The proposed method in this work is applied to the modified IEEE 39-bus system and to another higher wind penetration system as IEEE 9-bus system.

The first part of the study in this thesis is devoted to the selection of suitable FACTS type and ranking method. Two methods of lines ranking are studied. The first one is based on the minimum voltage allowed and the other method is based on the maximum lines over load. The results show that **<u>TCSC with capacitive range is the best solution for this problem,</u>** as it allows the system to operate without violating the power, voltage and power angle limits. Also it reduces the total loss of the system which gives wind generator more spare to cover its generation variation. Also it increases the minimum voltage to acceptable limit which is considered as an improvement in voltage profile. Results also proved that **<u>the ranking</u>**

according to the minimum voltage allowed better cost saving and better power system performance than the other method of ranking.

After the selection is fulfilled, the second part, which deals with maximizing the wind energy penetration of the system by using TCSC is performed under several topologies of system. This is based on the first model of wind generator. In this model the wind generator is considered as a generator producing besides the active power a reactive power within 33% of the active power. Three case studies of the system are considered: system without change; system with reduction of the impedance of the lines connected to the wind generator by 50% and system with the location of wind generator transferred to another location which has more interconnection with the network.

Finally 100% increase of wind generation is done by another way, by adding new wind generator at the bus which has more interconnection to the system. Results show that optimal TCSC allocation with reduction of the impedance of the line connected to the wind generator by 50% **has increased the wind power penetration by 170 % of its normal generation without violating the system parameters. It is also shown that multi location of wind generation, if possible, is better than wind generation penetration in the same location.**

Other studies are carried out to increase wind penetration based on the second and third model of wind generation (The generator produces active power and doesn't inject any reactive power to the network and a generator produces active power and consumes reactive power respectively). The results show that TCSC with capacitive range is the best solution for this problem. It can cover the required reactive power by the wind generation while keeping the system operate without power, voltage and power angle limits violated. Moreover, reactive power needed according to the grid code can be covered by using TCSC. Furthermore TCSC can achieve good cost saving in addition to the enhancement of operation of the wind generator.

Finally, in model 3 of wind, studies are carried out on a modified IEEE 9-bus system which has higher wind penetration more than before, with change in reactive power injection to the wind bus from the network. Results verify that TCSC with capacitive range is still the best solution for the problems associated with wind penetration.