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A Framework for Operation and Control of Smart Grids with Distributed Generation

ABSTRACT

The current status of distributed generation technologies and Flexible AC Transmissions (FACTS) Technologies is reviewed. Then this paper discusses a framework for operation and control of smart grids with distributed generation and FACTS in which two controls such as voltage control and stability control are included. In light of the different time scale requirements of voltage control and stability control, a global coordinated strategy is proposed for voltage control while a decentralized control strategy is utilized for stability control. Within these two controls, the ways of the participation of distributed generation and FACTS, for instance, in voltage control and stability control are discussed in order to make the power grids smart in terms of operation flexibility and enhanced control capability.

Keywords: *Smart Grid, Power System Control, Power System Stability, Flexible AC Transmission Systems (FACTS), HVDC, Distributed Generation, Wind Generation, Decentralized Control, Coordinated Control, Global Control*

1. Introduction

It has been recognized that increased demand along with uncertainty of transactions will bring extreme strain to power systems. Moreover large amounts of distributed generation, in particular wind generation, connected with the network will result in further uncertainty of load and power flow distribution and impose additional strain on electricity networks. It is a real challenge to ensure that the electricity system is flexible enough to meet new and less predictable supply and demand conditions in competitive electricity markets while making systems stable.

FACTS (Flexible AC Transmission Systems) devices [1–3] are considered as low-environmental-impact technologies and are a proven enabling solution for rapidly enhancing reliability and upgrading transmission capacity on a long-term cost-effective basis. Power flowing in the network is usually uncontrolled, and is governed by Kirchhoff's laws and Ohm's law. The uncontrollable power flows may result in bottlenecks in the network; loop flows; and angle and voltage instabilities, etc. The power angle and voltage instabilities may cause generator outages, line tripping and system blackouts.

Normally an electric power system should be operated within its operating limits such as voltage limits, thermal limits, and angle and voltage stability limits. FACTS and HVDC can provide both steady state and dynamic control for power systems. For steady state control, FACTS and HVDC can provide voltage regulation; power flow management and control; congestion management; and enhancement of transfer capability, etc. For dynamic control, FACTS and HVDC can provide fast voltage support; fast power flow control and dynamic congestion management; fast control of power oscillations; voltage stability control; and fault ride-through, etc.

Technologies such as FACTS and HVDC [1–3], HTS (High-Temperature Superconductor) cable [4], SMES (Superconducting Magnetic Energy Storage) [5] and FCL (Fault-Current Limiter) [6] together with Wide Area Stability Monitoring, Control and Protection System [7] are available to prevent or mitigate the kinds of outages that have happened in North America and in Europe in the past few years. It is anticipated that with the application of these devices either individually or in combination it should lead to a much more secure and reliable power grid. In addition to the application of FACTS and HVDC in system voltage, power flow and stability controls, FACTS and HVDC will also play a very important role in distributed generation interconnections, voltage and power flow controls of wind power networks, enhancement of the power quality and fault ride through capability, etc.

2. Distributed Generation

Distributed generation technologies includes reciprocat-

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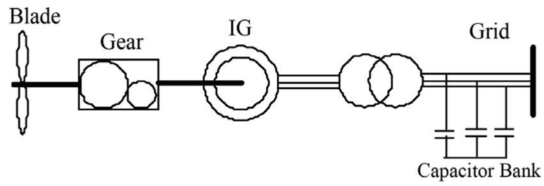
ing engines, micro-turbines, combustion gas turbines (including miniturbines), fuel cells, photovoltaics, and wind turbines. Generally, individual wind turbines are grouped into wind farms containing several turbines. Many wind farms are MW scale, ranging from a few MW to tens of MW. Normally distributed generation including wind farms or smaller wind projects may be connected directly to LV and MV electricity distribution systems while large distributed generation (larger wind farms) can often be connected to EHV distribution networks or even transmission networks. In the past, several types of WTs have been developed, among which three types of WTs such as WT with Induction Generator (IG), WT with doubly fed induction generator (DFIG), and WT with the Direct-Drive Permanent Magnet Generator (DDPMG) are very popular in practical applications. The basic configurations of the wind generation systems are shown in Figure 1.

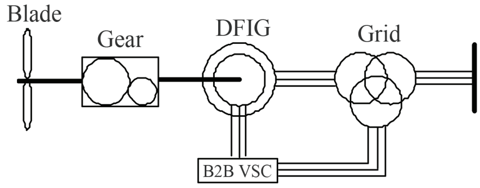
At the early stage of the development of WT techniques, the WT with IG was the dominated type of WT installed in wind farms. WT with IG is a fix-speed type of WT. The maximum power of such WT can not be tracked, and its efficiency is low. Since the squirrel cage induction machine is employed, the WT with IG always absorbs the reactive power from the power grid. These operating characteristics have an adverse effect on the stability of power systems, especially on the voltage stability of power systems. In recent years, the WT with DFIG has been developed very quickly, and most of the WTs installed in the past five years have been equipped with this type of WT. Basically, the WT with DFIG is a variable-speed type of WT, its efficiency has been improved compared with the WT with IG. The stator of the DFIG is connected to the power grid directly while its rotor winding is fed back from the stator winding by controlled back to back voltage source converters. The control of the WT with DFIG is flexible where the active power and the reactive power of the WT with DFIG can be controlled independently. With the development of the permanent magnet generator, the WT with DDPMG has attracted more and more engineering interest. The WT with DDPMG is a full-variable-speed WT, and it has the highest efficiency among the WTs developed, especially when the WTs operate at a low speed. Since the permanent magnet generator is driven directly by the WT, the gearbox is eliminated. Hence the maintenance cost for the WT with DDPMG is lower than that for the other types of WTs. Due to the fact that the rotor of the permanent magnet generator is made of permanent magnet material, the excitation system is not required, which leads to a simple controller for the permanent magnet generator. As the WT with DDPMG normally interfaces with the power grid via a full-scale frequency converter, the interaction between the generator and the grid is not as large as the WTs interfacing with the grid directly. Distributed wind generation including DFIG and DDPMG with power electronic converters can provide them the capability of voltage and stability control. With suitable control frameworks, DG such as DFIG and DDPMG can be used to control network voltage and stability actively. This will be discussed in later sections.

Blade IG Grid Gear



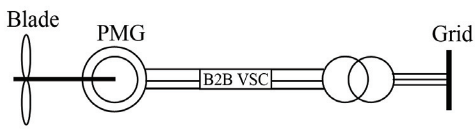
a

Blade DFIG Grid



b

Blade PMG Grid



C

Figure 1. Configuration of the WT systems

a. Configuration of WT with IG
b. Configuration of WT with DFIG
c. Configuration of WT with DDPMG

3. Facts Technologies

3.1 FACTS and HVDC Controllers

There are two categories of FACTS devices available. Thyristor switched and/or controlled capacitors/reactors such as SVC (Static Var Compensator) and TCSC (Thyristor Controlled Series Compensator) were introduced in the late 1970s while Voltage-Sourced Converter-based FACTS devices such as STATCOM (Static Synchronous Compensator), SSSC (Static Synchronous Series Compensator) and UPFC (Unified Power Flow Controller) were introduced in the mid 1980s. In the past, there has been a large number of SVCs installed in electric utilities. There are tens of conventional line commutated BTB (Back-to-Back) HVDC, a number of STATCOM and TCSC, three UPFCs, one IPFC and a number of VSC HVDC with BTB configuration installed within electric power systems around the World. It is anticipated that more STATCOM and VSC HVDC will be installed in the future.

All FACTS devices and HVDC links are helpful in stability control of power systems. The shunt type FACTS device is more useful to control system voltage and reactive power while the series type FACTS device is more suitable for power flow control. The series-shunt type controller-UPFC can be used to control the active and reactive power flow of a transmission line and bus voltage independently. The series-series type FACTS controller–IPFC (Interline Power Flow Controller) can be used to control power flows of two transmission lines while the active power between the two transmission lines can be exchanged. The newly developed VSC HVDC, which has similar control capability as that of the UPFC, can control both the independent active and reactive power flows of a transmission line and the voltage of a local bus [8]. However, the HVDC based conventional line commutated converter technique cannot provide voltage control and independent reactive power flow control. Another very important feature of VSC HVDC technique is that it can be very easily configured into a multi-terminal VSC HVDC. Research indicates VSC HVDC is a viable alternative to the UPFC for the purpose of network power flow and voltage control.

FACTS devices based on VSC techniques can be interconnected to implement various configurations and structures for different control purposes. While thyristor switched and/or controlled capacitors/reactors have limited performance and functionality, converter-based devices have superior performance, versatile functionality and various configuration possibilities. One shortcoming with converter-based devices is, they are more expensive. With the continuous effort in R&D, it is likely that the costs of converter-based devices will be reduced further, and hence they will be more widely used in the next 5 years.

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3.2 Advanced FACTS and HVDC Based Control for Smart Grids

It has been recognized that some transmission systems are not yet designed for the deregulated energy market. Power system infrastructure needs modernization as future power systems will have to be smart, fault tolerant, dynamically and statically controllable, and energy efficient. FACTS and HVDC will be helpful to provide fast dynamic voltage, power flow and stability control of the power grid while enhancing efficient utilization of transmission assets. At the same time network congestion will be efficiently managed and system blackouts will be mitigated or avoided. In order to deal with the uncertainty of demand and generation, relocatable FACTS controllers have been developed [9].

3.3 Integration of Wind Area Stability Control and Protection with FACTS and HVDC Control against System Blackouts

The wide area stability control and protection system is considered the "eyes" that overlook the entire system area, and can capture any system incidents very quickly; while FACTS and HVDC are the "hands" of the system, which have very fast dynamic response capability and should be able to take very quick actions as soon as commands are received from the system operator. As the current situation stands, the fast dynamic control capability of FACTS and HVDC has not been fully explored and realized. The integration of the Wide Area Stability Control and Protection with FACTS and HVDC control will fully employ control capabilities of both technologies to achieve fast stability control of system, and to prevent the system against blackouts. Hence, a high network securityand a reliable performance can be achieved.

In order to tackle large-scale stability disturbance, a coordinated control of the integrated power network is required using the advanced stability control methodologies and/or wide area monitoring and control by using FACTS and HVDC control technologies.

4. A Framework for Operation and Control of V Smart Rids with Distributed Generation

4.1. Voltage Control

For efficient, secure and reliable operation of electric power systems, it has been recognized that the following operating objectives should be satisfied: (a) Bus voltage magnitudes should be within acceptable limits; (b) System transient stability and voltage stability can usually be enhanced by proper voltage control and reactive power management; (c) The reactive power flows should be minimized such that the active and reactive power losses can be reduced. In addition, the by-product of the minimized reactive power flows can actually reduce the voltage drop across transmission lines and transformers.

In electrical power systems, voltage control and VAR management requires various voltage control devices installed at different locations of the systems. In addition to the voltage control devices, suitable control algorithms and software tools are needed to determine control settings of and coordinate the control actions of the voltage control devices sited at different locations of the systems. Basically the voltage control devices include shunt reactors and shunt capacitors, tap-changing transformers, synchronous condensers, synchronous generators, SVS, Converter-based FACTS controllers such as STATCOM, SSSC, UPFC, IPFC, GUPFC and HVDC light. Basically, the Converter-based FACTS have excellent dynamic reactive power and voltage control capability.

Optimal Power Flow (OPF) is security and economic control-based optimization, which selects actions to minimize an objective function subject to specific operating constraints. Most OPF programs can perform more than one specific function. One of the OPF applications in Energy Management Systems is to minimize active power transmission losses while control of reactive power from generator and compensating devices and control of tap-changing transformers are scheduled and coordinated. The voltage control and VAR management by OPF tends to reduce circulating VAR flows, thereby promoting flatter voltage profiles.

4.2 Stability Control

To maximize the benefits of FACTS technologies, much effort has been put to investigate the control capability of such devices to improve system stability. It has been proved that FACTS devices can provide positive add-on damping for small signal disturbance if proper damping controllers have been designed. The ideas of design approaches of conventional Power System Stabilizer (PSS) have been applied to the design of FACTS damping controllers. However, as FACTS devices are usually installed in transmission lines, this makes the damping controller design more challenging. For example, there may be difficulties in selecting feedback signals, in finding damping torque paths and so on. In recent years, Linear Matrix Inequality (LMI) technique has attracted much attention in the design of FACTS based damping controllers. The LMI technique has also been proposed for the design of robust damping control of FACTS, for example, $H\infty$ mixed-sensitivity [10,11], and mixed $H2/H\infty$ with pole placement [12]. LMI based computational algorithms, which are different from the traditional analysis tools, have been widely investigated in system and control areas [13]. In [14], a new two-step LMI approach has been applied for design of output feedback damping controller for a multi-model system considering multiple operating points. This approach has been applied to design of STATCOM damping controller with consideration of STATCOM internal controllers.

4.3 A Framework for Operation and Control of Smart Grids with Distributed Generation

Basically voltage control can be done at a relative slow time scale while stability control should be considered at a fast time scale. In current practice, voltage control by conventional power plants can be coordinated via SCADA/EMS systems. With the introduction of DG into electricity networks, the following voltage control framework may be considered:

1) Control Scheme a: Coordinated voltage control by conventional power plants and reactive control resources such as transformers, mechanically switched capacitors/reactors, FACTS while DG maintains the power factor at the Grid Entry point. For this control scheme, DG is very much like a load, and responds to the grid passively. This reflects the current practice.

2) Control Scheme b: Coordinated voltage control by conventional power plants and reactive control resources

such as transformers, mechanically switched capacitors/reactors, FACTS while DG maintains the voltage at the Grid Entry point. For this control scheme, DG is more actively participating in voltage control which such a control is still not coordinated. The may be done in the future as long as Grid Code is allowed.

3) Control Scheme c: Coordinated voltage control by conventional power plants and reactive control resources such as transformers, mechanically switched capacitors/reactors, FACTS and DG. For this control scheme, DG is fully participating in voltage control in a coordinated ways while DG or a group of DG can be operated very much like a conventional power plants with active control or management. This feature will be very important to work towards smart grids.

Stability control and voltage control can be done at different scales. For DG, these controls can be actually decoupled with the decoupled converter controllers.

With the introduction of DG into electricity networks,the following stability control framework may be considered:

1) Control Scheme a: Decentralized stability control by conventional power plants, FACTS and DG [15]. This reflects the current practice working towards smart grids.

2) Control Scheme b: Decentralized stability control by conventional power plants, FACTS and DG while some global control feedback signals. This reflects the future trend working towards smart grids.

3) Control Scheme c: Decentralized stability control by conventional power plants, FACTS and DG while coordinated control can be done through wide area measurement based technologies [14]. This reflects the future technologies for smart grids.

Numerical examples will be presented to show the control frame for voltage and stability control.

5 Conclusions

This paper has discussed the framework for operation and control of smart grids with distributed generation, in which two controls such as steady state voltage control and stability control are included. In light of the different time scale requirements of steady state voltage control and stability control, a global coordinated strategy is proposed for voltage control while a decentralized control strategy is utilized for stability control. Within these two controls, the ways of the participation of distributed generation in system control, for instance, wind generation and FACTS in voltage control and stability control have been discussed in order to make the power grids smart in terms of operation flexibility and enhanced control capability.

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