Role of FACTS devices in enhancing integration of renewable energy sources to the grid: a review

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Abstract

The modern power system is facing challenges such as exponential growth in demand, constrained infrastructure and deregulation of electricity markets. For a sustainable energy system, it is necessary to meet energy need by utilizing renewable energy sources (RES), which have minimum environmental impact. Over the last two decades, renewable energy generation and integration into the grid has received a lot of attention worldwide. In 2017 alone, more than half of all new electricity capacity installed globally was from RES. However, RES such as solar photovoltaic and wind energy are intermittent in nature. Integrating variable generating sources into the grid can cause problems such as voltage fluctuations and interruptions, which affect the performance of utility equipment as well as end user. Over the years, flexible AC transmission system (FACTS) device utilization in power systems has been on the rise. FACTS refer to the application of power semi-conductor devices to control electrical variables, thus influencing power flow and enhancing power system security. This paper investigates the role of FACTS devices in expediting renewable energy integration in power systems. Challenges associated with renewable energy injection into the grid, and how FACTS devices can mitigate these issues is presented. We conclude that the penetration rate of renewable energy will be accelerated if FACTS devices are incorporated in RES integration projects.

***Keywords*:** FACTS devices, RES, DFIG, WTG.

Introduction

During the last three decades, environmental concerns and the continuous depletion of fossil fuel reserves have spurred significant interest in utilization of renewable energy resources. Market liberalization and government’s incentives have further accelerated growth in the renewable energy sector.

Renewable energy is generally derived from either solar, wind, hydro, geothermal or biomass. These technologies offer a clean and free fuel source, but are intermittent in nature [1]-[4]. The European wind energy association (EWEA) has estimated that by 2020, 12% of the electricity demand for the whole world will be met by wind generation [5]. Over the last three decades, wind turbines have significantly evolved.

In terms of size, large wind turbines ranging from 1.5MW to 5MW appeared first in the EU, US and now China, and India utility grids. Currently, wind turbines rated above 10MW are under extensive research and development. Larger wind turbines are more efficient because the rotor is located higher above the ground, such that they intercept higher velocity winds [6][7]. The wind power resource is intermittent in nature.

Interconnecting intermittent sources to the utility grid on a large scale could affect the voltage and frequency control. Based on weather forecasts, it is possible to predict the mean wind speed in short term period, but not dynamic changes which take place around a base speed [3][8]. Wind power projects are located in areas with high wind speeds, often in rural zones with relatively weak electrical networks.

To facilitate wind power evacuation from remote areas to regional grids, new transmission lines have to be constructed. This takes stringent environmental approvals, huge investment cost and a long construction time [9]-[14]. As the wind turbine size increases, power electronic based controllers such as FACTS devices which offer fast switching operations can be exploited [15]-[17].

Various studies have been conducted relating to the use of FACTS devices in wind energy integration. Kumar et al in [2] present a STATCOM-BESS to cancel out the harmonic parts of the load current and also support the reactive power demand for a WTG. A STATCOM-BESS system was also employed by Sheeraz and Brijesh in [17] to improve the voltage profile and reduce harmonic distortion in a wind power plant. Yasmeena and Das in [18] develop a hybrid fuzzy logic controller (FLC) based STATCOM which significantly reduces the THD in utility current from 27.21% to 0.21%.

Similar findings are presented by Tareen et al in [19], where an active power filter STATCOM is installed in the IEEE 519 bus system and the THD in utility voltage reduces from 39.48% to 4.2%. Nidhi and Amit in [14] utilize the UPFC to maintain the desired voltage at point of common coupling (PCC), thereby maintaining the WTG in service during and after a fault.

Sant et al in [20] compare the performance of STATCOM and UPFC in integrating a wind farm into the grid and conclude that UPFC utilization presents a more stable voltage during fault as compared with the STATCOM. In other studies, Jyoti et al in [5] develop a fuzzy logic controller which uses MPPT technique to extract maximum power from a WTG, whereas Xiaohu et al in [16] investigate the optimal location of a variable series reactor (VSR) and phase shifting transformer (PST) in a transmission network considering high penetration of wind power.

This paper brings out the challenges encountered in integrating wind energy into the grid, and how FACTS devices can be utilized in their mitigation. In section 2, we present wind power generation technologies, whereas the challenges in RE integration are given in section 3. An overview of FACTS devices is outlined in section 4 whereas in section 5 we give the applications of FACTS devices in wind power integration. The conclusions is presented in section 6.

Wind Power Generation

Wind turbines generate electrical power in the same way as all other generation technologies. A wind turbine consists of the main tower, blades and the nacelle as shown in Fig. 1.

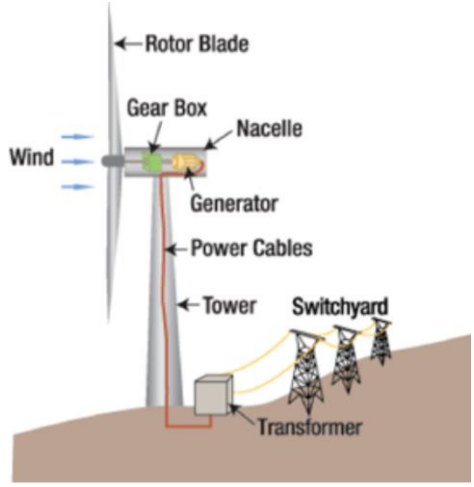

Fig.1: Main parts of a modern wind turbine

The Nacelle houses electrical and mechanical components of the turbine. Wind passes over the blades exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotation speed for the generator.

Using electromagnetic induction, the generator converts the kinetic energy into electrical energy. The power output goes to a transformer, which transforms the voltage to the right one for the distribution system. Inside the Nacelle is an anemometer, wind vane, and controller that read the speed and direction of the wind. As the wind changes direction, the yaw motor turns the nacelle so the blades are always facing the wind [21]- [22].

Types of wind turbines

There are two basic types of wind turbines:

Horizontal axis wind turbine

Nearly all the wind turbines currently in use are horizontal axis turbines. All the components (blades, shaft, generator) are mounted on top of a tower as shown in Fig. 2, and the blades face into the wind. The shaft is horizontal to the ground. Wind hits the blades which are connected to a shaft causing rotation.

Fig. 2: Horizontal axis wind turbine

Vertical axis wind turbines

Vertical axis turbines have blades that are attached to the top and the bottom of a vertical rotor as shown in Fig. 3. The wind turbine is near the ground, unlike horizontal where everything is on a tower. Very few vertical axis wind turbines are in use today because they do not perform as well as horizontal axis turbines [22].

Fig. 3: Vertical axis wind turbine

The power produced by a wind turbine is related to the wind speed at the moment. A power curve for a wind turbine, shown in Fig. 4, indicates the power produced across the entire operating range. Most wind turbines start generating electricity at wind speeds of 3-4m/s; generate maximum (rated) power at around 15m/s; and shut down to prevent storm damage at 25m/s [22].

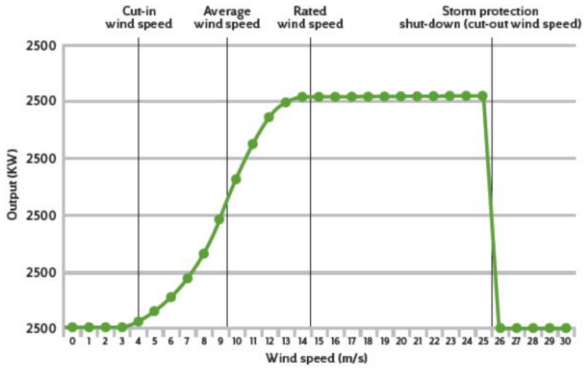

Fig. 4: Typical power curve of a 2.5MW turbine

Wind turbine generators

AC generators fall into two basic categories: synchronous and asynchronous.

Asynchronous (induction) generators

Induction generators fall into two types: fixed speed induction generators (FSIGs) with squirrel cage rotors (SCIGs) and doubly fed induction generators (DFIGs) with wound rotors.

Fixed speed squirrel-cage induction generator (SCIGs)

Squirrel cage induction generators were used in early fixed speed wind turbine designs. They consisted of the rotor, a SCIG and a gearbox interconnection. As shown in Fig 5, the generator stator winding is connected to the grid.

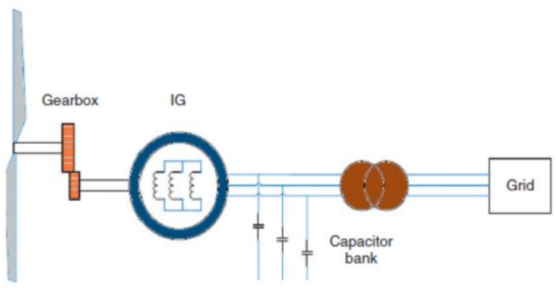

Fig. 5: Squirrel cage induction generator

The generator slip varies with generated power, so the speed is not, in fact, constant; however, as the speed variations are very small (just 1-2%), it is commonly referred to as a fixed speed turbine. Since a squirrel cage generator always draws reactive power from the grid, this is undesirable, especially in weak networks. The reactive power consumption of SCIGs is therefore always compensated by capacitors [18] [23].

Doubly fed induction generator (DFIG)

A doubly fed induction generator is basically a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter.

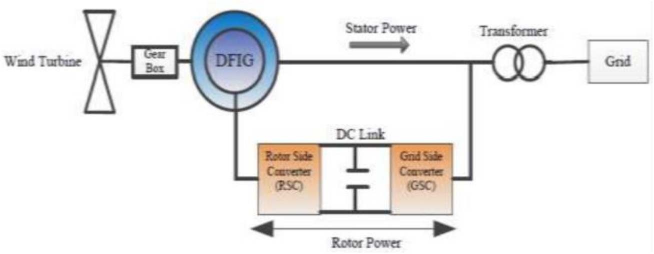

Fig. 6: Geared DFIG generator

The converter consists of the rotor side and the grid side. These voltage source converters use forced commutated power electronic devices to synthesize an AC voltage from a DC source. The grid side converter (GSC) keeps the DC link voltage constant, whereas the rotor side converter (RSC) maintains the rotor speed constant regardless of the wind speed.

The control system generates the pitch angle command signals and the voltage command signals for the converters in order to control the power of the wind turbine, the DC voltage, and the voltage at grid terminals. The DFIG offers the advantage of separate active and reactive power control. Over 85% of installed wind turbines utilize DFIGs [23] [24].

Synchronous generators

Coupling a synchronous generator directly to the grid is carried out using full size power converters. The generator is either connected directly to the turbine rotor operating at low rotating speeds or uses a single stage gearbox and operates at medium speeds. It has a large number of poles with classical excitation or PMs. Due to the large number of poles and low rotating speed, the generator must develop large torque, so it must have large weight and diameter [6] [9].

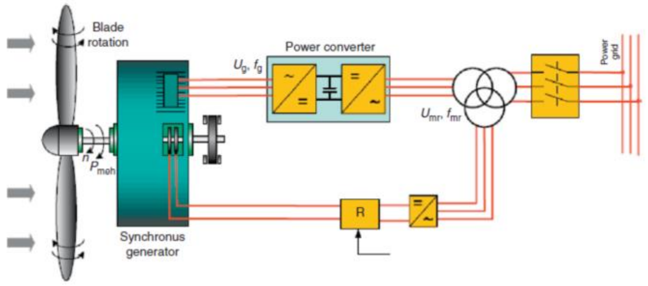

Fig. 7: Direct drive synchronous generator

Challenges with wind power integration

The main challenges associated with wind power injection in power grids arise because RES depend on weather and environmental factors. The most significant challenges include inability to forecast their output, ride through capability whenever a fault arises, and power quality problems [6].

Forecasting

Being able to forecast the wind energy output is critical. Accurate forecasting of their output can significantly reduce required reserve margins and ensure economic operation of power systems. Lately, the wind resource has become more predictable, with a margin of uncertainty of about 5% in a time period of 72 hours. This uncertainty further decreases for a shorter time interval, leading to improved dispatchability of the wind power plants [3] [12].

Fault ride through

When a fault occurs, asynchronous wind generators demand more reactive power from the grid, worsening the voltage levels across the network. If the wind penetration is high, and it is not supported by adequate dynamic reactive power reserve, wind generators will disconnect from the grid as their terminal voltage falls below the voltage specification.

On the other hand, a voltage swell could occur when a large amount of load is disconnected from the grid within a very short time span. To solve this issue, WTGs are usually switched off during voltage swells. However, with increased penetration of RES in power networks, switching off large number of wind generators can lead to frequency stability issues.

The modern grid code requires WTGs to have reactive power compensation capability. This ensures uninterrupted operation of the WTGs in the presence of network disturbances [4] [25].

Power quality

In wind energy generating plants, power quality is primarily concerned with the quality of current waveform being drawn or generated by the wind turbine. Generally, power quality issues result in the malfunction of equipment, may cause tripping of contactors and, tripping of protection devices. The main power quality issues related to wind power integration include voltage and frequency variations, and interruptions [2] [17].

Voltage variations

These are classified into:

Voltage fluctuation – changes in voltage amplitude such as voltage sag and voltage swell due to the fluctuation of power output from wind turbines.

Flicker – voltage fluctuation between 90% and 110% of nominal value.

Voltage transient – short duration burst of energy usually caused by a sudden change of state, such as capacitor switching.

Harmonics – currents or voltages with frequencies that are integer multiples of the fundamental power frequency. Harmonics result due to operation of power electronic converters [18] [26].

Power frequency variation

This is the deviation of the power system fundamental frequency from its specified nominal value. In an electric power system, frequency is an indicator of the balance or imbalance between the generated and absorbed active power. During normal functioning, the power output from a wind power plant can vary up to 15% of the installed capacity in a 15 minute span. This can cause an additional imbalance between the power generated and consumed in the system [25].

Interruptions

This can result due to the decrease or increase of the voltage or load current for a very short period of time. Such interruptions can cause malfunction in data processing equipment.

To maintain power system stability, wind farms must be able to provide voltage and reactive power control, frequency control and fault ride through capability. Reactive power compensation equipment such as capacitor banks, condensers and FACTS devices can be used to achieve power quality [17].

Power electronics in wind turbines

Power electronics are finding an increasing use in the modern wind turbines. In the variable speed systems, the generator is normally connected to the grid via a power electronic system. In fixed speed systems, power electronics aim at smooth connection-disconnection from the grid, and for compensation of reactive power consumption. These two requirements are met by the use of soft starters and capacitor banks.

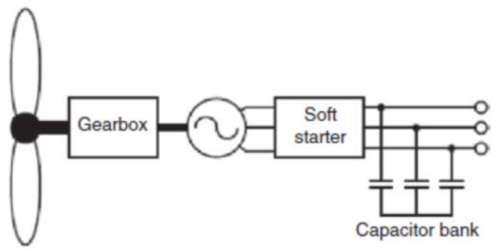

Fig. 8: Power electronics in modern wind turbine

The soft starter is an electronic device aiming at reducing transient currents during connection or disconnection from the grid. Using thyristors controlled by their firing angle, the generator is smoothly connected to the grid over a predefined number of steps. AC capacitor banks are used for reactive power support [24].

Introduction to FACTS devices

With significant RES being integrated into the grid, controllability, reactive power compensation and system stability have become major concerns for grid operators. Conventional power flow control devices consist of fixed or mechanically switched components such as resistors, inductors or capacitors, and transformers.

Modern power flow controllers such as flexible AC transmission systems (FACTS) devices also contain these components, but use additional converters to switch components in smaller steps during an AC cycle. FACTS devices modify the bus voltage magnitude, transmission line reactance and transmission angle, to influence the power flow [27]- [29].

Depending on how these devices are connected to the power system, they are classified into shunt, series or combined shunt and series devices.

Shunt FACTS devices

Shunt FACTS devices are mainly used for reactive power compensation and voltage control. The two most commonly used FACTS devices are the static VAr compensator (SVC) and the static synchronous compensator (STATCOM).

Static VAr compensator (SVC)

In the 1970s, the first generation of FACTS devices, known as the SVC was introduced. An SVC is a shunt connected device capable of supplying or absorbing reactive power to support a specified voltage magnitude at the high voltage side of its connecting transformer. As shown in Fig. 9, the SVC comprises a bank of thyristor controlled reactors (TCR) in parallel with a bank of thyristor switched capacitors (TSC) [30].

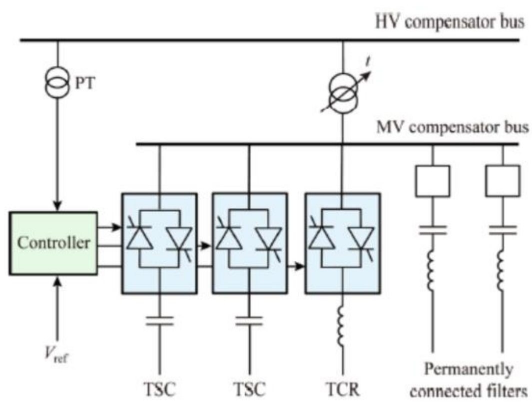

Fig. 9: SVC schematic representation

The TCR consumes VAr from the system to lower the voltage if the reactive load is capacitive. On the other hand, if the reactive load of the system is inductive, the TSC banks are switched in to inject reactive power, which in turn raises the system voltage. The thyristor pairs operate as switches which enable the SVC to respond quickly to network changes [31].

Static synchronous compensator (STATCOM)

The STATCOM is the modern counterpart of the SVC, whose main function is to supply or absorb reactive power to support a specified voltage magnitude at the high voltage side of its connecting transformer. The STATCOM, as shown in Fig.10, is made up of the VSC, the smoothing inductor, the interfacing transformer and PWM control system [30].

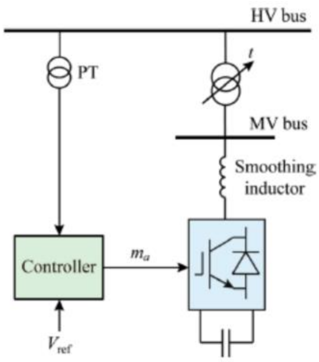

Fig. 10: STATCOM schematic representation

The VSC converts DC input voltage into AC output voltage. When the inverter output voltage is higher than the system line voltage, the STATCOM generates reactive power. If inverter output voltage is lower than system line voltage, the STATCOM absorbs VArs from the system. The STATCOM is therefore able to control its output voltage independently of the AC system voltage. The smoothing inductor is used between the VSC and the step-up transformer to eliminate the harmonics [28] [31].

Series FACTS devices

Series FACTS devices are usually connected in series with the transmission line to influence the line impedance thus control power flow. The two most common series connected FACTS devices are the thyristor-controlled series compensator (TCSC) and the static synchronous series compensator (SSSC).

Thyristor controlled series compensator (TCSC)

The TCSC is a series FACTS device in which a capacitor is inserted in series with the transmission line, and a thyristor-controlled reactor is connected in parallel with the capacitor as shown in Fig. 11.

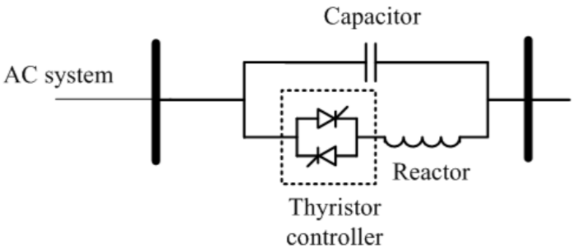

Fig. 11: TCSC schematic representation

By adjusting the firing angle of the thyristors, the capacitive reactance is smoothly varied over a wide range, thus line reactance is modified. Depending on the firing angle, the TCSC may operate in capacitive or inductive modes. The TCSC is increasingly finding use in long transmission lines for increasing line loadability, mitigating sub-synchronous resonance and damping power oscillations [33].

Static synchronous series compensator (SSSC)

The SSSC is the series counterpart of the STATCOM. It consists of a VSC connected to the transmission line through a series coupling transformer as shown in Fig. 12.

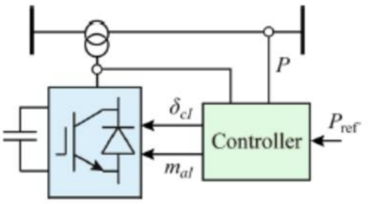

Fig. 12: SSSC schematic representation

The DC capacitor fed VSC generates a three phase voltage at fundamental frequency, which is then injected in the transmission line through a series transformer. The injected voltage is of a controllable magnitude and phase angle, hence control of active and reactive power flow in the network is possible. Unlike the TCSC, the SSSC does not remarkably affect the impedance of the transmission system, hence there is no danger of having resonance problems [27] [30].

Combined series and shunt FACTS devices

Combined series and shunt FACTS devices can vary multiple system parameters simultaneously, such as the bus voltage magnitude and angle, and the transmission line reactance. The most commonly used device is the unified power flow controller (UPFC).

Unified power flow controller (UPFC)

The UPFC is a compound equipment with two VSCs connected in shunt and series, as shown in Fig. 13.

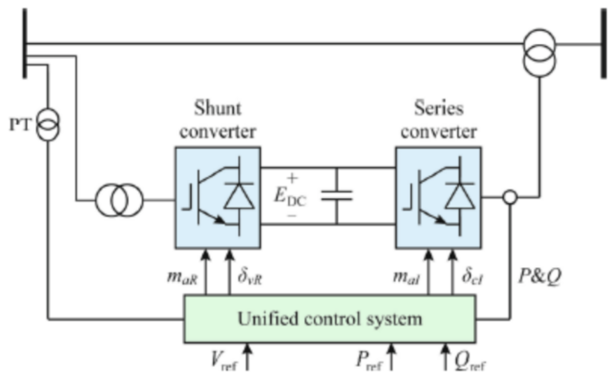

Fig. 13: UPFC schematic representation

The DC side of the two converters is connected through a common capacitor which provides DC voltage for the converter operation. The series converter injects an AC voltage with controllable magnitude and phase angle in series with the transmission line via a series transformer.

The shunt converter provides the active power demand of the series converter at the common DC link. It also provides shunt compensation for the line. The UPFC thus allows exchange of active and reactive power with the transmission line [31] [33].

Distributed FACTS (D-FACTS)

A new concept of D-FACTS is being investigated, as an alternative solution to the main problem of FACTS devices, which is the huge capital cost. D-FACTS present many potential benefits since they are smaller and less expensive than conventional FACTS devices. Deployment of low power D-FACTS devices will provide an affordable method for enhancing controllability, asset utilization, and power quality enhancement, with little environmental impact [27] [31].

FACTS devices in wind power integration

In an attempt to overcome the dynamic impacts caused by wind speed changes, FACTS devices can be used as interfaces between the grid and the intermittent sources. Series devices can be employed on the transmission system while shunt devices can be deployed either in the transmission network, generation side or load buses. Various roles of FACTS devices in wind power integration include:

1. *Reactive power compensation*

FACTS devices can be connected at the point of common connection (PCC) or some other place for reactive power support of the power grid. This practice started with the incorporation of STATCOMs into older generations of wind farms based on fixed speed induction machines. The aim was to dynamically provide reactive power support to ensure wind generators could satisfy voltage ride through capability imposed by new grid codes.

FACTS devices can also be used to mitigate voltage fluctuations of the wind generator [21] [27].

2. Power system stability improvement

Wind power plants are often placed in remote areas and power evacuated using long transmission lines. If reactive power compensation is not sufficient, generated active power might need to be limited to avoid instability. Shunt FACTS devices applied at PCC of such a plant greatly enhances system voltage stability. It is beneficial to compensate VAr demand using FACTS devices without relying on WTG capabilities, since their control is faster in case of centralized coordination. FACTS devices can also be used to contribute to short term frequency support by providing synthetic inertia. Synthetic inertia can reduce the frequency variations as wind power fluctuates [9] [30].

3. Voltage ride through capability

Earlier, WTGs were usually disconnected from the grid amid fault conditions, so as to avoid any possible damages to wind turbines. With increased penetration of wind power, sudden disconnection of WTGs could result in poor grid stability. FACTS devices can be employed to ensure reliable power delivery to the grid during abnormal operating situations. Ongoing studies are looking into how energy storage systems (ESS) can be incorporated in wind power projects to cushion the imbalance between generated wind power and power supplied to the grid [14] [34].

4. Power flow control capability

With the power flow control capability introduced by FACTS devices, transmission bottlenecks can be avoided through shifting the power from the congested lines to the underutilized lines nearby. Series FACTS devices have been key enablers for very high penetration of renewables due to their capabilities in continuously controlling power flows in transmission lines [16].

5. Power quality improvement

FACTS devices can be used to mitigate power quality problems such voltage and frequency variations, interruptions, poor power factor and harmonics. Owing to the increasing penetration of RES, FACTS devices can be used to ensure harmonious integration of intermittent sources into existing transmission networks [19].

Conclusions

Increasing penetration of RES, growing demand, limited resources and deregulated electricity markets have posed new challenges to the operation and control of modern electric power systems. This paper presents the application of FACTS devices to enhance integration of wind power into power systems.

As higher levels of intermittent sources are integrated into electric power systems, the technical challenges revolve around variability, reliability and asynchronous operation. Incorporation of FACTS devices in wind power plants is promising since these devices help in improving system stability, enhancing ride through capability, regulating power flow, and power quality improvement.

The performance of thyristor based FACTS devices is limited by the system operating conditions. Therefore, VSC based FACTS devices such as the STATCOM, SSSC or UPFC are more attractive since their operation is not dependent on grid conditions. However, these devices are substantially expensive than the conventional devices. D-FACTS are also being explored to extend the effectiveness of FACTS devices and accelerate their adoption in low cost schemes.

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