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Technology of VAr Compensators for Induction Generator Applications in Wind Energy Conversion Systems

Many of today utility interconnected wind farms use induction generator (IG) to convert the captured wind mechanical power into electricity. Induction generator has some advantages over the synchronous generator (SG). The main advantages are its robustness and its capability to be synchronized directly to the grid. The main disadvantage, however, is its dependency on the grid for supplying its own reactive power 'VAr'. Whether fixed or adjustable VAr systems are connected across its terminal, IG must operate at unity power factor at the rated loading while the wind power varies. With supervised control and appropriate coordination, VAr can be used to the benefits of both the wind farm developer and the hosting utility. The incorporation of today adjustable reactive power compensators such as the Static VAr Compensation (SVC) and Static Synchronous Compensator (STATCOM) with IG are vital ingredient toward a successful penetration of wind energy in today distribution grid to ensure voltage stability during the steady state and transient periods.

Keywords: Induction generators, Static VAr compensators, Wind energy, Wind farms.

1. INTRODUCTION

Wind energy conversion systems (WECS) are considered to be a viable contribution to the energy industry. In addition to the environmental benefits, WECS penetration increases the utility's reserve capacity by adding converted wind power into electricity. WECS can provide power to remote areas therefore, relieving the generating and distribution utilities from expanding their resources. They can also be integrated with existing transmission or distribution networks. When WECS are connected to the distribution network -grid integrated- ancillary services are likely to be supplied by the hosting utility, which can impose stress, cost and increase the network vulnerability to instabilities. Grid integrated WECS must meet the hosting utility integration requirements and adhere to the strict safety and protection procedures [1]-[3]. Large number of WECS forms wind farms 'wind power plants' are made of either inland or offshore wind turbine generating units. Global installed wind generation capacity has increased from 2,500 megawatts (MW) in 1992 to to more than 59,000 MW by June 2006, at an annual growth rate of near 30%. Almost three quarters of this capacity has been installed in Europe. European Wind Energy Association (EWEA) scenarios show that the future prospects of the global wind industry are promising and the total wind power installed worldwide could quadruple to 160,000 MW by 2012 [4]. Penetration levels in the electricity sector have reached 20% in Denmark. The German state of Schleswig-Holstein has 1,800 MW of installed wind capacity, enough to meet 30% of the region's total electricity demand, while in Navarra, in Spain, 50% of consumption is met by wind power. Also In 2003, the global wind-generated electricity was estimated around 67 TWh of electricity [5].

Many of today utility interconnected wind farms use the induction generator to convert the captured wind mechanical power into electricity. Induction generator has some advantages over the synchronous generator. The main advantages are its robustness and its capability to be synchronized directly to the grid. The main disadvantage, however, is its dependency on the grid for supplying its own reactive power ‘VAr’. For using WECS with induction generators configuration, the grid has to supply not only the load and lines reactive power but also the generator. There are strict requirements from the hosting utility when it comes to consume reactive power as it negatively affects the whole network by increasing the losses and reduce the grid voltage. It is therefore very important to meet the variable VAr requirements within the wind farm locality and to relieve the hosting utility from supplying extra VAr’s.

2. WIND ENERGY INDUCTION GENERATORS ‘WEIG’ SCHEMES

Induction generators (IG) consume reactive power to establish the magnetic field in which its quantity depends on the magnetizing element, operating speed as well as supplied load. Even at zero active power ‘P’, the generator require up to 25% of its rating as a reactive power. This is evident by examining an induction generator characteristic as the operating slip is varied by 10% above the synchronous speed as shown in Figure 1.

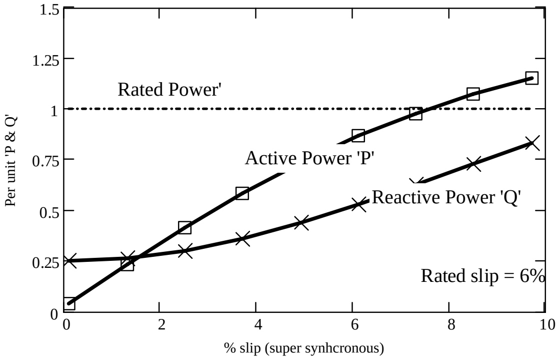
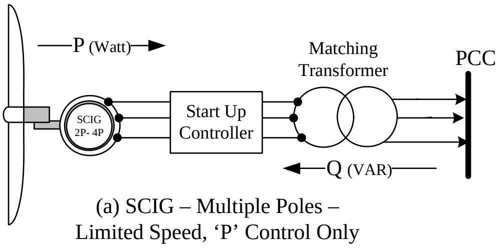


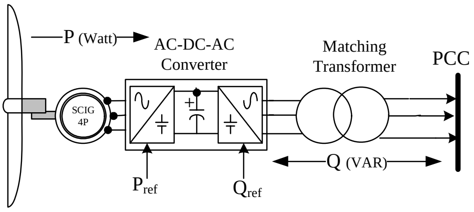
Figure 1 Induction Generator Active ‘P’ and Reactive ‘Q’ Power Relation Versus the % Slip above the Synchronous Speed.

Integration with the utility grid takes many configurations that depend on the used electronic conversion system. There are two types of IG’s used the wind industry depending on how the rotor is manufactured and its conductors are connected. These are the squirrel cage induction generator (SCIG) where the rotor conductors are shorted and the wound rotor induction generator (WRIG) where the rotor conductors are connected to slip rings allowing access to the rotor circuitry. WRIG allows power to flow from the stator as well as the rotor to recovery some of the otherwise dissipated slip power. Both types can be configured to operate under constant or variable speed modes and controllability of generated power. The key advantages of variable speed WECS compared to fixed-speed WECS is reduced mechanical stress and improvement in the conversion efficiency at higher capital and maintenance cost [6], [7]. Fixed speed WECS have the capability of regulating the wind turbine rotational speed to a fixed value by mechanical means and, therefore, enabling a standard synchronous generator or SCIG to be directly coupled to the turbine and produce standard grid voltage frequency when the later is driven above the synchronous speed.

SCIG are reported to be almost 23% of the world market and are used mostly in the fixed speed WECS. Figure 2 show how SCIG could be tied to the grid. In Figure 2(a), SCIG is configured to supply power to the grid under two speed settings. The generator will have two sets of poles (2 poles and 4 poles). As long as the generator slip is limited to 5% above the synchronous speed, the voltage and frequency follows the grid values, however, the reactive power has to be supplied by the grid. A second SCIG that uses one set of poles and provides a wider slip range control is shown in Figure 2(b). The increase in the speed range is achieved by using power converter that regulate the flow of power and maintain the voltage and frequency within the grid limits. This scheme can provide some support of the reactive power as it has a capacitor in the dc link of the AC-DC-AC converter. But still, it will rely on the grid to support the varying reactive power that cannot be met by the converter [8].



(a) SCIG – Multiple Poles – Limited Speed, 'P' Control Only

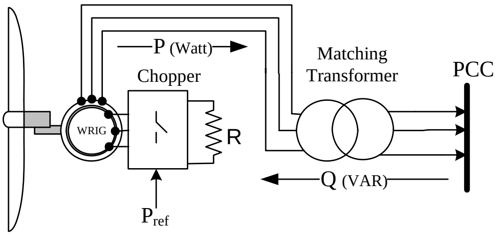


(b) SCIG – Variable Speed, 'P & Q' Control

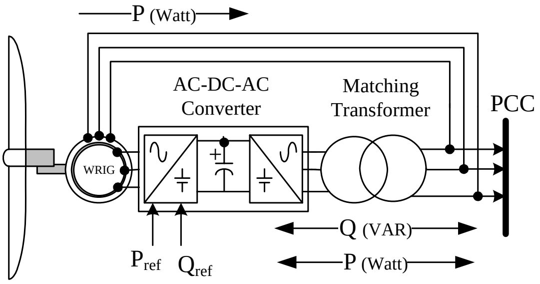
Figure 2: SCIG Grid connected WECS.

Variable speed WECS allows the turbine to rotate at different rotational speeds 'to match the maximum allowable wind velocity/power path' thus maximizing the energy capturing process. This production category comprises almost 50% of the world market. Generally the generator coupled to the turbine is WRIG designed to run at below (sub) or above (super) synchronous speed and that is depending on the converter control configuration. In general, the generated voltage and frequency are regulated electronically using power electronic conversion devices, which are either connected to the stator side 'fully rated' or at the rotor side 'fractionally rated'. Figure 3 show how WRIG could be tied to the grid.

A simple, yet effective way to control the generated power is to increase externally the rotor windings resistance as shown in Figure 3(a). The external resistance can be controlled by a transistorized chopper to allow the slip to vary with the wind speed [9]. The power is allowed only to flow from the stator side. A more accurate control at a wider range is the slip energy recovery scheme shown in Figure (3(b). Here WRIG feeds power from the stationary side and from the rotor when driven above the synchronous speed. The power converter is connected to the rotor side and is rated at a fraction of the generator power as it only handle the power flowing in or out the rotor side which is a function of the operating %slip [10]. WRIG output capability increases when power is allowed to flow from either side of the generator. In both schemes an additional power factor correction capacitors are normally connected across the generator terminal to support the need of large reactive power requirements situations.



(a) WRIG- Rotor Resistance Control



(b) WRIG- Slip Energy Recovery “Double Fed”, ‘P’ and ‘Q’ Control

Figure 3: WRIG Grid connected WECS.

It is evident form the various schemes that the IG must have adequate reactive power source capable of running the system at various wind velocity. Many hosting utilities require that WECS operator to provide a proper means to compensate for the reactive power continuously drawn from the grid and maintain a healthy power factor at the point of power injection. Reactive power compensator is therefore a very important aspect of WECS reliability whether for one or a group of wind turbines.

The paper looks at the various technologies used for compensating the reactive power requirements to the individual generator and to a cluster of generator forming a wind farm. The following section introduces the various application of the induction generator in wind energy conversion systems. It is followed by presenting the various types of VAr compensators technologies. Finally the paper will look at the most practical reactive compensation system that can be employed in wind farms.

3. WEIG REACTIVE POWER COMPENSATION TECHNIQUES

The majority of VAr compensators used in many of today WEIG systems employ shunt type compensators. The compensators are either connected at the individual WT or grouped at a centralized point of connection to the hosting utilities. The focus of the following sections will address the different types of the shunt VAr compensators that are used in today wind farms.

3.1 Shunt type VAr Compensators

There are diverse devices employed for smoothly controlling reactive power requirements, among them for the purposes of discussion are:

1. Static VAr Compensation (SVC)

2. Static Synchronous Compensator (STATCOM)
3. Unified Power Flow Controller (UPFC)'

The above listed systems are composed of power electronic switching devices controlling capacitive and inductive passive elements. Tuned filters are normally incorporated to minimize the reflection of harmonics into the grid. Solid state and computerized controlled VAr's such as SVC and STATCOM and other emerging topologies are known in the industry as Flexible Alternating Current Transmission Systems (FACTS).

3.1.1 Static VAr Compensator (SVC)'SVC'

There are two basics techniques to compensate for the reactive power using solid state power switching devices. The power electronics devices are either the naturally or gate forced commutated thyristor 'GTO' or more recently using the insulated gate bipolar transistors (IGBT). The electronic devices are configured to control the passive elements such as air-cored reactors and the high voltage power capacitors. Circuit elements can be configured to provide fixed, adjustable/controllable VAr sources.

A- Fixed VAr compensation is achieved by shunt capacitors connected in parallel across the WECS 'injection point'. Shunt capacitors can be switched to meet varying levels of VAr requirements to maintain good level of voltage regulation and power factor using binary switched capacitors, as shown in Figure 4. For constant active power flow and supply voltage of V_{rms}, the required capacitive VAr is the difference between the pre compensation VAr and the required compensated VAr as given by equation 1.

$$VAr(capacitive) = VAr(required) - VAr(Uncompensated) \tag{1}$$

The amount of the capacitive susceptance B_{Cap} is then given by equation 2:

$$B_{Cap} = \frac{VAr(\mathrm{Re}\,quired) - VAr(Uncompensated)}{{V_{rms}}^2} \text{ Siemens} \tag{2}$$

From which the required capacitance value in Farad is given by using equation 3.

$$C\,(Farad) = \frac{B_{Cap}}{(2\pi f)} \tag{3}$$

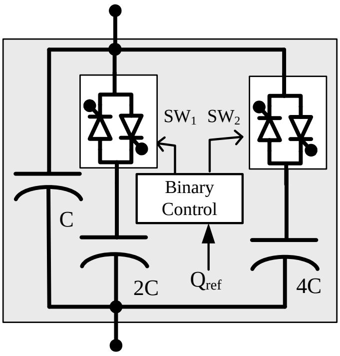


Figure 4: Binary switched capacitive VAr controller.

The capacitor must be disconnected when it is not needed at light loads to avoid self-excitation of the IG particularly when the grid is disconnected while its shaft is rotating.

Series reactors are normally tuned with shunt capacitors to eliminate undesired current harmonics and to act as an inrush current limiting during switching of the capacitors. Such configuration is a low cost and only provides leading power. The disadvantages being the occurrence of switching transient as different values of capacitors are switched on and off.

B- Controllable 'dynamic' VAr sources are generated by using SVC that allow the compensator current be varied form from leading to lagging values by changing the terminal reactance by the use of controlled capacitive and inductive elements connected in parallel at the point of power feed i.e. point of common coupling (PCC). The delay of current with the respect to the voltage is carried out by using static semiconductor devices such as thyristor and power transistors. There are four practical electronically controlled and switched SVC's:

1. Thyristor switched capacitor (TSC)'
2. Thyristor controlled reactor (TCR)'
3. Fixed capacitor-thyristor controlled reactance (FC-TCR)'
4. Thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR)

B1- Thyristor switched capacitor (TSC)'

TSC configuration is shown in Figure 5(a). The switching device in TSC is used only to switch ON or OFF the switched capacitor banks, and no phase angle control is used. TSC by itself does not produce harmonics but may very well produce switching transients. The switching of the capacitor are used when load demand capacitive support. This capacitive power support is usually divided into 3 or 4 steps. The total switched susceptance for n branches, assuming all branches have equal capacitances, seen by the system is given by equation 4:

$$B_C\,total = \sum_{1}^{n} B_{Cap} \text{ Siemens} \tag{4}$$

In general series reactor is connected in series with capacitor bank to limit the inrush while switching capacitor and to limit the rate of rise of current of switching device to a safe valve.

B2- Thyristor controlled reactor (TCR)'

In the TCR configuration, the static switch is connected in series with the reactor as shown in Figure 5(b). TCR acts like a variable susceptance and is dependent on Thyristor switching control. By phase angle control of switch from 90^o to 180^o, the flow of current through the reactor is varied. The fundamental inductor current is therefore a function of the branch susceptance (B_{TCR}( )) that is dependent on the firing delay angle ( ) and is estimated by using equation 5 [14]:

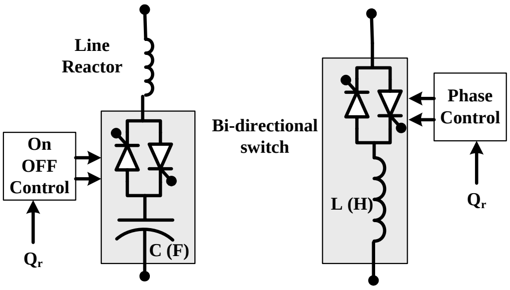
$$I_{fund}(\alpha) = V_{rms}\,.\,B_{TCR}(\alpha)\text{ A} \tag{5}$$

Where

$$B_{TCR}(\alpha) = B_{\max}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin(2\alpha)}{\pi}\right) \quad \text{Siemens}$$

$$and$$

$$B_{\max} = \frac{1}{(2\pi f)L}; \quad f\,\text{is frequency (Hz)} \quad \text{and} \quad L\,\text{is the inductance (H)}$$



(a) TSC 'one arm' **(b) TCR 'one arm'**

Figure 5: Controllable VAr 'TSC and TCR' elements.

In three-phase arrangement, TCR is normally delta connected as the harmonic components in reactor current are flowing into the network will be 3rd, 5th, 7th, 9th, 11th and 13th with maximum amplitude of 13.8%, 5%, 2.5%, l.6%, 1% and 0.7% respectively of reactor fundamental current. If the network is balanced all the multiples of 3rd harmonic will be blocked in the delta connected TCR and will not flow in the network. It is also to be noted that in the case of unbalanced load, multiples of 3rd harmonic currents (3rd, 9th harmonics) also flow into network in addition to other odd harmonics. Hence filter capacity has to be increased while filtering the undesired harmonics created by TCR during its operation.

B3- Fixed capacitor and thyristor-controlled reactor (FC-TCR)

It must be noted that TSC by itself cannot provide smooth variable reactive power. Control is possible only in steps. Step-less reactive power control is therefore achieved by operating TCR bank in conjunction with TSC with additional filter banks required to filter out harmonic currents. In this configuration a fixed capacitor is connected across a combination of series connected switching device and a reactor capacitor as shown in Figure 6. The current in the reactor is varied by the previously discussed method of firing delay angle control. The fixed capacitor in practice is usually substituted, fully or partially, by a filter network that has the necessary capacitive impedance at the fundamental frequency to generate the VAr required, but it provides low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR. The fixed leading VAr supplied by the capacitor is opposed by the variable lagging VAr consumed by the reactor to yield the required net VAr. The total susceptance seen by the system is made of two parts (fixed and variable) and is given by equation 6

$$B_{FC-TCR}(\alpha) = B_{Cap} + B_{TCR}(\alpha) \quad \text{Siemens} \tag{6}$$

In the presence of coupling step-down transformer between the utility network and the SVC unit, the total susceptance can be varied by the firing delay angle with a minimum (inductive, = 90^{o}) and maximum (capacitive, = 180 ^{o}) values given by equation (7) and (8) respectively

$$B_{FC-TCR}(\alpha)_{\min} = \frac{(B_{Cap} + B_{ind})\, B_{Transformer}}{(B_{Cap} + B_{ind}) + B_{Transformer}} \quad \text{Siemens} \tag{7}$$

$$B_{FC-TCR}(\alpha)_{\max} = \frac{B_{Cap}\, B_{Transformer}}{B_{Cap} + B_{Transformer}} \quad \text{Siemens} \tag{8}$$

Where $B_{\text{Transformer}}$ is the coupling transformer susceptance.

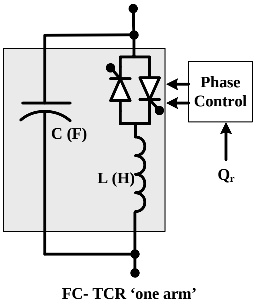


Figure 6: Controllable VAr using FC-TCR elements

At the maximum capacitive output, the thyristor-controlled reactor is off. To decrease the capacitive output, the current in the reactor is increased by decreasing delay angle. At zero VAr output, the capacitive and inductive currents are made equal. With a further decrease of the delay angle (assuming that the rating of the reactor is greater than that of the capacitor), the inductive current becomes larger than the capacitive current, resulting in a net inductive VAr output.

B4- Thyristor-switched capacitor and thyristor-controlled reactor (TSC-TCR)

TSC-TCR is similar to the operation of the FC-TCR but with stepped values of capacitors. A single-phase TSC-TCR is shown in Figure 7. For a given capacitive output range, it consists of multiple numbers of TSC branches and one TCR. The number of branches is determined by practical considerations that include the operating voltage level, maximum VAr output, current rating of the switching devices, etc. Of course, the inductive range also can be expanded to any maximum rating by employing additional TCR branches. The total capacitive output range is divided into 'n' intervals. In the first interval, the output of the VAr generator is controllable in the zero to 'VAr/n' range, where VAr, is the total rating provided by all TSC branches. In this interval, one capacitor bank is switched in and, simultaneously, the current in the TCR is set by the appropriate firing delay angle so that the sum of the VAr output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required. The total susceptance seen by the system through coupling transformer is given by equation 8;

$$B_{TSC-TCR}(\alpha)=\frac{(B_{Cap..n}+B_{TCR}(\alpha))\,B_{Transformer}}{(B_{Cap..n}+B_{TCR}(\alpha)+B_{Transformer}}\quad \text{Siemens} \qquad (9)$$

Where $B_{Cap\ldots n}$ is the susceptance caused by switching n number of capacitors

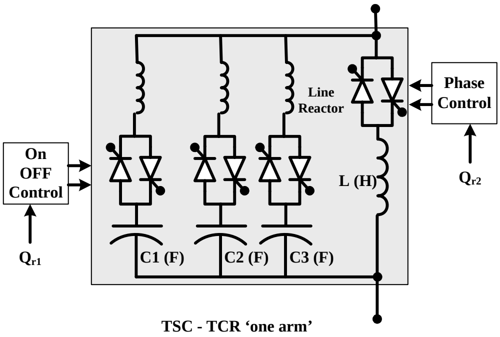


Figure 7: Controllable VAr using TSC-TCR elements.

The change in the bus voltage due to SVC operation is given by equation 10. Here the change in the bus voltage is a function of the susceptance (B_{SVC}), supply voltage (Vs) and the effective short circuit ratio (ESCR) given as the ratio between the change in the fundamental component of the SVC voltage over the change in the fundamental component of the SVC drawn current;

$$\Delta V = \frac{Vs \, . \, B_{SVC}}{ESCR} \tag{10}$$

Where

$$ESCR = \frac{1}{\left(\dfrac{-\Delta V_{fund-SVC}}{\Delta I_{fund\_SVC}} \right)}$$

3.1.2 Static Synchronous Compensator

STATCOM is made of six power electronics switching devices in a three phase full bridge configuration. The rectified voltage output is powering dc voltage capacitor. The converter is connected in shunt to the distribution network through a limiting reactors or coupling transformer as shown in Figure 8.

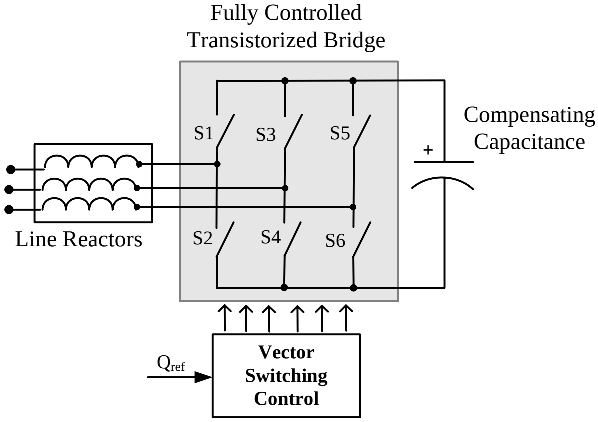


Figure 8: STATCOM configuration.

When system voltage is larger than the fundamental line voltage of the converter, the SVC generates reactive power, and when system voltage is higher, it absorbs reactive power [14]. This configuration allows the device to absorb or generate controllable reactive power with an apparent capacitive or inductive current absorbed by the controlling bridge and is independent of the AC line voltage. The fundamental converter voltage is controlled by switching on and off the electronic devices, thus the voltage across the capacitor is controllable and in turn the capacitive susceptance seen by the supplying network. The switching devices are forced commutated devices such as gate turn off thyristor (GTO) and the insulated gate bipolar transistor (IGBT) due to its lower switching losses and reduced size. Moreover, the power rating of these devices is relatively low. The most commonly used type is the capacitor controlled STATCOM voltage source converter.

The control strategy is to rapidly switch ‘few kHz’ the devices on and off to generate variable pulse width modulated (PWM) voltage across the capacitor. This in turn results in a pulse modulate line voltage with variable magnitude and phase presented by a large fundamental component and a handful of high frequency harmonics. The high frequency harmonic components can be easily filtered using high frequency tuned passive elements. As the fundamental component of the line voltage varies so the current drawn by the converter.

3.1.3 Unified Power Flow Controller

UPFC basically consists of two fully controlled converters sharing a common DC link, as shown in Figure 9. Converter 2 performs the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line [15]. Converter 1, on the other hand, supply or absorb the active power demanded by Converter 2. A simple way to shed light on the active and reactive power handled by converter 1 is to look at the d-q axis components influencing the active and reactive power injection. Assuming that converter 1 is a sinusoidal voltage source allowing bi-directional power flow; the instantaneous active and reactive power is then given by equation 11 and 12 respectively.

$$P_{active}(t)=\frac{3}{2}v_d\,.i_d \tag{11}$$

$$Q_{reactive}(t)=\frac{3}{2}v_d\,.i_q \tag{12}$$

where; subscript ‘d’ and ‘q’ denotes to the direct and quadrature components of the voltage and current in the synchronously rotating frame transformation.

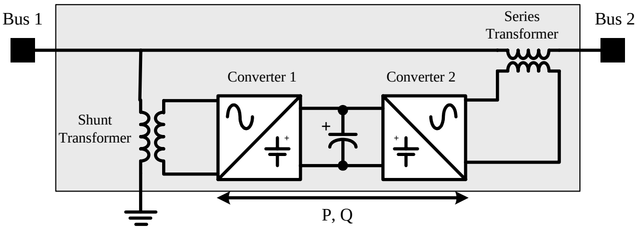


Figure 9: Unified Power Flow Controllers.

Both converters can be controlled to generate or absorb controllable reactive power or provide independent shunt reactive compensation for the line. In principle, a UPFC can perform voltage support, power flow control and dynamic stability improvement in one and the same device.

4. WIND FARMS AND REACTIVE POWER REQUIREMENTS

Wind farms are arrays of WECS’s interconnected electrically so as to deliver cumulative power to the utility grid [16]. From an electrical power flow perspective, the wind farm acts in parallel with the utility's conventional generating capacity to supply the power demands of the connected load. The requirement to reactive power compensation is that the wind farm reactive power is neutral with a tolerance of plus or minus 10% of the farm rated active power. Wind farms are made of tens to hundreds of machines with a combined wind farm power rating of thousands to tens of megawatts. Some wind farms incorporate only one design of wind turbine. Others have a various makes, models, control, generators and ratings. Some wind farms incorporate variable speed WRIG doubly fed units in order to have control on the active and reactive power flow thus minimizing the need for centralized VAr controller [17]. Usually, the power rating of the wind farm is a small fraction of the conventional generation capacity on the grid, typically known as the wind penetration ratio. In general the ratio of wind generating capacity to that of the total capacity (wind plus conventional) serving utility load at any given moment is measured by the wind penetration which currently does not exceeds 15% for many of the existing wind farms. Unfortunately, wind farms can not be treated as independent power generating source mainly because the generated power is intermittence, are located away from the load centers, have a low capacity factor and are undispatchable. Moreover, conventional generation largely uses synchronous generators, which are able to continue to operate during severe voltage transients produced by transmission system faults. This capacity can not be demonstrated for SCIG without the use of sophisticated power electronics interface. One of the big issue when dealing with wind farms is how the farm reacts on short circuits and the influence of rapidly changing voltage that may cause flicker. It is logical to expect therefore, from a wind farm to provide some degree of redundancy as conventional power plants to meet some of the transmission losses, reactive power demand and fault ride ability.

The main purpose, however, of establishing a wind farm is to considerably smooth the generated output relative to that of a single turbine and to collect as much as of the wind energy within one locality. Many of today wind farms incorporate sophisticated supervisory control and data acquisition system (SCADA) for coordination with its own units and with the hosting utility. The degree of smoothing depends on the geographical extent of the wind farm, average wind speed, the control characteristics of the wind turbines and, finally, details of the terrain and how they influence the distribution of wind speeds across the wind farm.

Depending on the wind farm generating unit type and control, a proper VAr controller must be effectively incorporated to meet the hosting utility safe operation and power delivery requirements [18], [19]. The need for reactive power control doesn’t stop individual IG. If a wind farm only has a SCIG then it would be expected that each individual IG should have its own VAr supply and must run at near unity power factor at full load.

The use of fixed type VAr across each individual generating unit would not be practical as the VAr level changes with the power delivered and may influence the system balanced nature as more leading VAr are injected at the PCC at no load. If that is the case, it is important then to include a centralized VAr such as SVC or a FACT system to regulate the system as the generating units output fluctuate. This will also be a good practice even for the wind farms that have mixed types of generating ‘SCIG and WRIG’ units as shown in Figure 10. The use of centralized VAr unit can also be used to maintain the hosting utility distribution network voltage within the limits as the distance between the wind farm and the point of feed may be long. If there are centralized VAr units installed, it should be carefully coordinated with the hosting utility be able to form effective part of the distribution power quality and stability of the system.

In many countries the minimum VAr capability of the wind generating system should not be less than 15% of active power rating to maintain high power factor and voltage control at the point of common coupling. This minimum threshold would obviously increase or decrease depending on the wind generator type and the VAr handling capacity of the distribution grid [20].

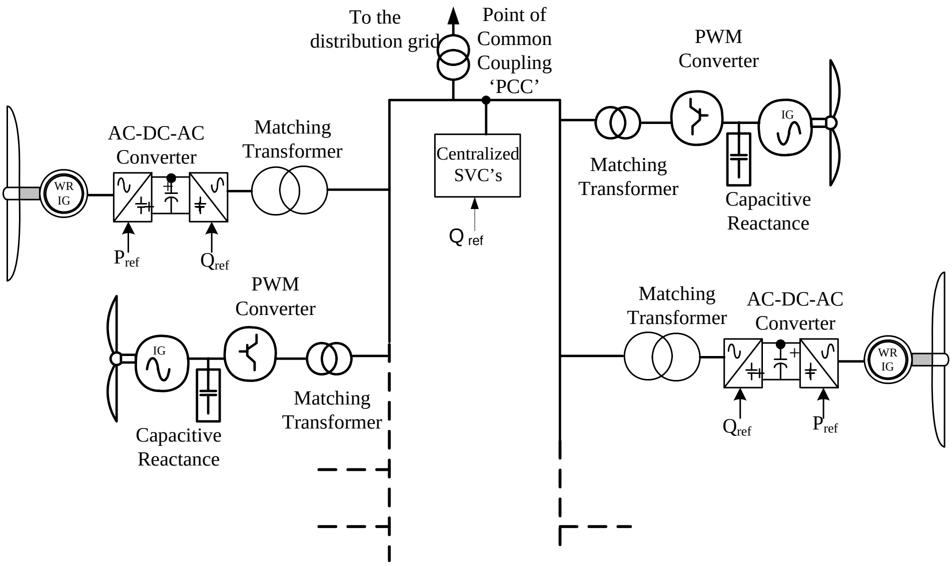


Figure 10: WECS grid integrated Wind Farms with mixed WT conversion systems.

5. CONCLUSION

This paper has reviewed the various technologies used for compensating the reactive power requirements to the individual generator and to a cluster of generators forming a wind farm. Installing centralized VAr compensator such as SVC, STATCOM or UPFC is important to maintain controllable reactive power flow between the generating units and the utility network. The centralized VAr controller is connected at the PCC to compensate for the connecting lines losses as well as regulating the fluctuated VAr demand and mitigate voltage flicker. There are various systems used by wind farm developers to supplement the VAr deficiency when using IG's among the most practical and cost effective systems are the emerging static VAr compensators such as VSC, STATCOM and UPFC. Dynamic compensation of reactive power is an effective means of safeguarding power quality as well as voltage stability. Finally great caution must be considered when dealing with VAr's in WEIG. VAr's compensators must have protection elements against the voltage and current handling capabilities.

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