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An Overview on Control of Variable Pitch and Variable Speed Direct-Drive Wind Turbines in Weak Grid Systems With Active Power Balance

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Abstract *– In the case of operating in a weak grid system, when wind power becomes a significant portion of the power system or even the sole energy source, the wind power generators and converters are expected to help maintain the grid voltage. The gridside converter needs to work as a voltage source to help regulate the terminal (grid) voltage amplitude and frequency by adjusting the reactive power and active power flow, respectively. For a direct-drive permanent magnet synchronous generator with a full power converter, the active power must be provided by the captured wind power. The active power flow between the source (captured wind power) and the grid (load) must be balanced by actively controlling the generator speed and wind turbine pitch angle. In the study, the coordinated control of generator speed and blade pitch angle is proposed together with a dc-link voltage controller.*

Keywords*: SCIG (squirrel cage induction generator), PCC (point of common coupling), DFIG (doubly-fed induction generator)*

I. Introduction

Now a days, mainly distributed generation (DG) from wind assets in medium voltage (MV) and low voltage (LV) sharing networks accounts for a comparatively small share of the largely power supplied by the networks. The network is typically supposed as an ideal energy source (strong grid) and the wind producer and power converter operates as a current resource, where the highest wind control is transferred to the physically powerful grid, subsequent MPPT (maximum power point tracking) method. This circumstance is likely to change in the near potential, as a great mechanism of wind power is encouraged in many countries for the reason that of the distinct profit they can offer: sustainability, emission-free etc. The space stuck between the wind farm and load centre is generally very long; the voltage drop for the reason that of the impendence of the transmission line will vary for dissimilar wind power and load circumstances. Correspondingly, the grid frequency also varies with power; in the case where the bus is not infinite (e.g. the generators connected to the grid are droop controlled). Therefore, the wind farm is in fact facing a weak grid, where the voltage of the point of common coupling (PCC) is not an ideal voltage source. In this case, when wind power becomes a significant portion of the power system or even the sole energy source, the wind power generator and its converter are expected to help maintain the grid voltage and frequency, operating like a conventional large synchronous generator (SG). The weak grid condition can also be a result of intentional separation or islanding from the grid, or grid faults (unintentional islanding). It applies as well to the stand-alone operating mode. Fig. 1a shows the structure of a typical weak grid system with wind turbines and local load as well as the transmission network. The bus which the system is connected to is assumed to have limited capacity with frequency droop characteristics. Each wind turbine adopts the topology of a full power converter and a direct-drive permanent magnet generator (PMG) as shown in Fig. 1b. Several papers have studied the converter stand-alone mode operation and power sharing between the load-side converters using droop control, assuming the converter dc-link voltage is constant with active power balance, without considering the source (wind) characteristics. In , the authors discussed the wind turbine active power control by changing the generator speed and do not include pitch control for adjusting the input power. In adopt the auxiliary load (damping resistor) to dissipate the excessive wind energy for power balancing purpose which is not practical for large wind turbines. This paper investigates several important issues for wind turbines operating in weak grid systems or stand-alone systems with a focus on active power balance control, which has not been well addressed before. The paper will first analyse the difference between wind turbine operating in a strong grid and a weak grid system. Then, the active power balancing issue between the source (wind) and the load is analysed. The coordinated control of generator speed and blade pitch angle is proposed to balance the active power flow, thus maintaining the converter dc-link voltage. Furthermore, the model and control method of the grid (load)-side inverter as a voltage source is described. Droop control is used to share the active power and reactive power between different wind turbine converters as well as with grid. The proposed control schemes are tested through simulation under three different scenarios concerning various load and wind conditions. With the proposed control scheme, the voltage quality at the PCC point has mbeen improved with the support of wind power. The active power balancing scheme between source and load as well as the power sharing between multiple wind turbines are achieved in weak-grid and stand-alone conditions.

II. Literature survey

Xibo Yuan et. al. [1] “Control of variable pitch and variable speed direct-drive wind turbines in weak grid systems with active power balance” In the case of operating in a weak grid system, when wind power becomes a significant portion of the power system or even the sole energy source, the wind power generators and converters are expected to help maintain the grid voltage. The gridside converter needs to work as a voltage source to help regulate the terminal (grid) voltage amplitude and frequency by adjusting the reactive power and active power flow, respectively. For a direct-drive permanent magnet synchronous generator with a full power converter, the active power must be provided by the captured wind power. The active power flow between the source (captured wind power) and the grid (load) must be balanced by actively controlling the generator speed and wind turbine pitch angle. In the study, the coordinated control of generator speed and blade pitch angle is proposed together with a dc-link voltage controller. A model of the grid-side converter operating as a voltage source has been built and the strategy regarding voltage and frequency regulation is presented. Simulation is carried out with different wind and load profile. The results show the wind energy can help support the weak grid and power the local grid in stand-alone mode as well. In a weak-grid system or stand-alone system, the captured wind power should be balanced with the load power, which can be achieved by the generator speed and turbine pitch control. By changing the generator speed, the captured wind power can be adjusted and the kinetic energy is stored or released accordingly, which is helpful for damping the load power change. The pitch control is coordinated with the generator speed control and is used for limiting the generator speed range. A well-designed dc-link voltage controller can maintain the active power flow balance between the source and load. The droop control is adopted for power sharing between multiple winds converters and also for regulating the grid voltage amplitude and frequency via reactive power and active power control. Simulation results have shown that the proposed system can help maintain the weak grid voltage and also power the local grid in stand-alone mode operation. The proposed scheme with active power control can also be used for wind power smoothing and other active power control applications.

Johan Morren et. al. [2] “Wind Turbines Emulating Inertia and Supporting Primary Frequency Control” The increasing penetration of variable-speed wind turbines in the electricity grid will result in a reduction of the number of connected conventional power plants. This will require changes in the way the grid frequency is controlled. In this letter, a method is proposed to let variable-speed wind turbines emulate inertia and support primary frequency control. The required power is obtained from the kinetic energy stored in the rotating mass of the turbine blades. The wind turbine operated at only0.35 p.u. The additional power that was generated for support was roughly 0.1 p.u. The ability of the wind turbine to support the primary frequency control will be better at higher power, because the kinetic energy stored in the blades will increase. During the support, the rotational speed of the wind turbine is decreasing. As a result, the power will drop considerable when the frequency control support is ended, as shown in Fig. 2(b). This drop in power will be undesirable mostly, especially when complete wind farms show this behavior. In larger wind farms, the effect can be mitigated partially by ending the frequency control support of the turbines at different times. Also a gradual change to normal operation, instead of the abrupt change that is applied in the example, will improve the behavior. The main conclusion that can be drawn from the results in this letter is that variable-speed wind turbines are able to support primary frequency control and to emulate inertia by applying additional control loops. For that purpose, the kinetic energy stored in the “hidden inertia” of the turbine blades is used.

K. De Brabandere et. al. [3] “A Voltage and Frequency Droop Control Method for Parallel Inverters” In this paper, a new control method for the parallel operation of one or several inverters in an island grid or the mains is described. Frequency and voltage control, including mitigation of voltage harmonics, are achieved without the need for any common control circuitry or communication between the inverters. Each inverter supplies a current that is the result of the voltage difference between a reference AC voltage source and the grid voltage across virtual impedance with real and/or imaginary parts. The reference AC voltage source is synchronised with the grid, with a phase shift, depending on the difference between nominal and real grid frequency. A detailed analysis show that this approach has superior behaviour in comparison with the existing droop control methods, considering the mitigation of voltage harmonics, short-circuit behaviour and, in the case of a non-negligeable line resistance, the ‘efficient’ control of frequency and voltage. Experiments show the behaviour of the method for an inverter feeding a highly distorted load and during the connection of two parallel inverters in operation. A new method for controlling voltage and frequency in island grids using parallel inverters is presented. By imitating a voltage source with complex finite-output impedance, voltage droop control is obtained. Frequency droop control results from synchronizing the power source with the grid, with a phase angle difference that depends on

Qing-Chang Zhong et. al. [4] “Static Synchronous Generators for Distributed Generation and Renewable Energy” In this paper, the idea of operating an inverter as a synchronous generator is developed after establishing a model for synchronous generators to cover all dynamics without any assumptions on the signals. The inverters which are operated in this way are called static synchronous generators (SSG). This means that the wellestablished theory/device for synchronous generators can still be used for inverters, which will dominate the power generation in the future because of the increasing share of distributed generation sources and renewable energy sources utilised. The power of an SSG can be regulated using the well-known frequency and voltage drooping mechanism. SSGs can also be easily operated in gridconnected mode or island mode. Simulation results are given to verify the idea. In this paper, the idea of operating an inverter as a synchronous generator has been developed after establishing a model for synchronous generators to cover all the dynamics without any assumptions to the signals. This model can be used to investigate the stability of power systems; in particular, those dominated by parallel converters in distributed generation. It has been shown that it is very easy to control the power delivered to the grid. Also, because of the built-in frequency and voltage drooping mechanism, these SSGs are able to share load automatically.

Mohammad N. Marwali et. al. [5] “Control of Distributed Generation Systems—Part I: Voltages and Currents Control” This paper discusses a digital control strategy for three-phase pulse-width modulation voltage inverters used in a single stand-alone ac distributed generation system. The proposed control strategy utilizes the perfect robust servo mechanism problem control theory to allow elimination of specified unwanted voltage harmonics from the output voltages under severe nonlinear load and to achieve fast recovery performance on load transient. This technique is combined with a discrete sliding mode current controller that provides fast current limiting capability necessary under overload or short circuit conditions. The proposed control strategy has been implemented on a digital signal processor system and experimentally tested on an 80-kVA prototype unit. The results showed the effectiveness of the proposed control algorithm. This paper has outlined the development of a digital control strategy for three-phase PWM inverters used in DGS applications. The control strategy combines the perfect RSP controller for low THD output voltages regulation and the discrete sliding mode current controller for fast over-current protection. The voltage controller was developed by including the dynamic of the current controller into the plant with the computation delay of the DSP accounted for. It was shown that by including the harmonic frequency mode to be eliminated into the perfect RSP controller, superior low THD performance could be achieved without sacrificing the transient recovery performance of the output voltages. The experimental results presented verified the effectiveness of the proposed control strategy both in providing low THD output voltages regulations and in providing protection under short circuit condition.

III. Method

The most commonly applied wind turbine designs can be categorized into four wind turbine concepts. The main differences between these concepts concern the generating system and the way in which the aerodynamic efficiency of the rotor is limited during above the rated value in order to prevent overloading. These concepts are presented in detail in the following paragraphs.

A. Fixed Speed Wind Turbines (WT Type A)

This configuration corresponds to the so called Danish concept that was very popular in 80’s. This wind turbine is fixed speed controlled machine, with asynchronous squirrel cage induction generator (SCIG) directly connected to the grid via a transformer as shown in Fig. 1. This concept needs a reactive power compensator to reduce (almost eliminate) the reactive power demand from the turbine generators to the grid. It is usually done by continuously switching capacitor banks following the production variation (5-25 steps) Smoother grid connection occurs by incorporating a soft-starter. Regardless the power control principle in a fixed speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and further into electrical power fluctuations. These can yield to voltage fluctuations at the point of connection in the case of a weak grid.

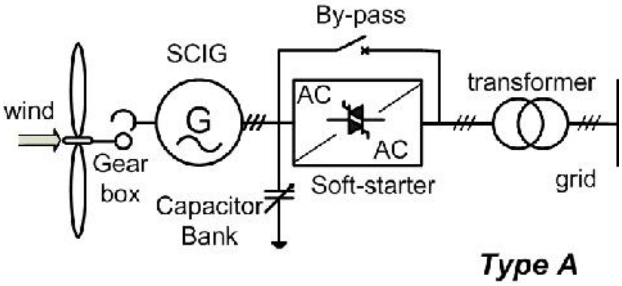

Fig. 1. Fixed speed wind turbine with directly grid connected Squirrel-cage induction generator.

Because of these voltage fluctuations, the fixed speed wind turbine draws varying amounts of reactive power from the utility grid (in the case of no capacitor bank), which increases both the voltage fluctuations and the line losses. Thus, the main drawbacks of this concept are: does not support any speed control, requires a stiff grid and its mechanical construction must be able to support high mechanical stress caused by wind gusts.

B. Partial Variable Speed Wind Turbine with Variable Rotor Resistance (WT Type B)

This configuration corresponds to the limited variable speed controlled wind turbine with variable rotor resistance, known as OptiSlip (VestasTM) as presented in Fig. 8. It uses a wound rotor induction generator (WRIG) and it has been used by the Danish manufacturer Vestas Wind Systems since the mid 1990's.

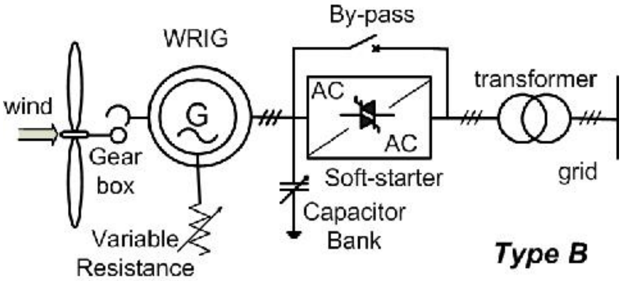

Fig. 2. Partial variable speed wind turbine with variable rotor Resistance

The generator is directly connected to the grid. The rotor winding of the generator is connected in series with a controlled resistance, whose size defines the range of the variable speed (typically 0-10% above synchronous speed). A capacitor bank performs the reactive power compensation and smooth grid connection occurs by means of a soft-starter. An extra resistance is added in the rotor circuit, which can be controlled by power electronics thus, the total rotor resistance is controllable and the slip and thus the power output in the system are controlled. The dynamic speed control range depends on the size of the variable rotor resistance. Typically the speed range is 0-10% above synchronous speed. The energy coming from the external power conversion unit is dumped as heat loss. In [26] an alternative concept using passive component instead of a power electronic converter is described. This concept achieves 10% slip, but it does not support a controllable slip.

C. Variable Speed WT with partial-scale frequency converter (WT Type C)

This configuration, known as the doubly-fed induction generator (DFIG) concept, corresponds to the variable speed controlled wind turbine with a wound rotor induction generator (WRIG) and partial-scale frequency converter (rated to approx. 30% of nominal generator power) on the rotor circuit as shown in Fig. 3.

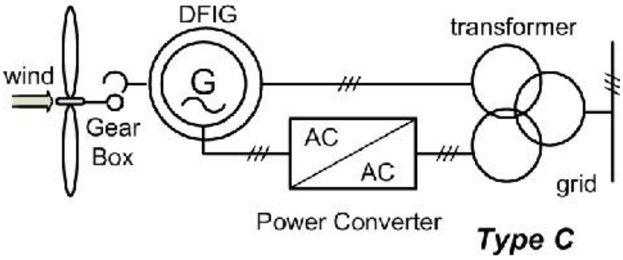

Fig. 3. Variable speed wind turbine with partial scale power converter.

The stator is directly connected to the grid, while a partial-scale power converter controls the rotor frequency and thus the rotor speed. The power rating of this partial-scale frequency converter defines the speed range (typically ±30% around synchronous speed). Moreover, this converter performs the reactive power compensation and a smooth grid connection. The control range of the rotor speed is wide compared to that of OptiSlip. Moreover, it captures the energy, which in the OptiSlip concept is burned off in the controllable rotor resistance. The smaller frequency converter makes this concept attractive from an economical point of view. Moreover, the power electronics is enabling the wind turbine to act as a more dynamic power source to the grid. However, its main drawbacks are the use of slip-rings and the protection schemes in the case of grid faults.

D. Variable Speed Wind Turbine with Full-scale Power Converter (WT Type D)

This configuration corresponds to the full variable speed controlled wind turbine, with the generator connected to the grid through a full-scale frequency converter as shown in Fig. 4. The frequency converter performs the reactive power compensation and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator WRSG) or permanent magnet excited type (permanent magnet synchronous generator PMSG). The stator windings are connected to the grid through a full-scale power converter. Some variable speed wind turbines systems are gearless – see dotted gearbox in Fig. 10. In these cases, a direct driven multi-pole generator is used. The wind turbine companies Enercon, Siemens Wind Power, Made and Lagerwey are examples of manufacturers using this configuration.

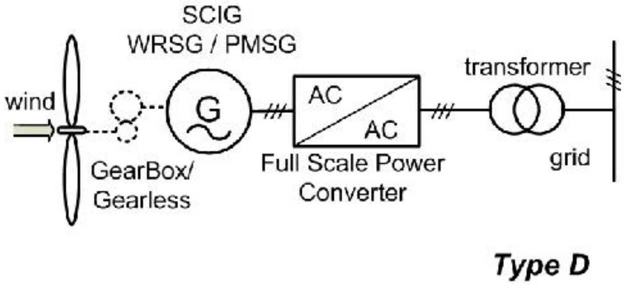

Fig. 4. Variable speed wind turbine with full-scale power Converter.

Basically two power converter topologies with full controllability of the generated voltage on the grid side are used currently in the wind turbine systems. These power converters are related with Type C and Type D wind turbine concepts. Initially, the main purpose of the multilevel converter was to achieve a higher voltage capability of the converters. As the ratings of the components increases and the switching- and conducting properties improve, the secondary effects of applying multilevel converters become more and more advantageous. The reduced content of harmonics in the input and output voltage as well as a reduced EMI is reported. The switching losses of the multilevel converter are another feature, which is often accentuated in literature. In it is stated, that for the same harmonic performance the switching frequency can be reduced to 25% of the switching frequency of a two-level converter. Even though the conduction losses are higher for the multilevel converter, the overall efficiency for the diode clamped multilevel converter is higher than the efficiency for a comparable two-level converter. Of course, the truth in this assertion depends on the ratio between the switching losses and the conduction losses.

IV. Conclusion

In a weak-grid system or stand-alone system, the captured wind power should be balanced with the load power, which can be achieved by the generator speed and turbine pitch control. By changing the generator speed, the captured wind power can be adjusted and the kinetic energy is stored or released accordingly, which is helpful for damping the load power change. The pitch control is coordinated with the generator speed control and is used for limiting the generator speed range. A well-designed dc-link voltage controller can maintain the active power flow balance between the source and load. The droop control is adopted for power sharing between multiple winds converters and also for regulating the grid voltage amplitude and frequency via reactive power and active power control. Simulation results have shown that the proposed system can help maintain the weak grid voltage and also power the local grid in stand-alone mode operation. The proposed scheme with active power control can also be used for wind power smoothing and other active power control application

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