A Review of Full Scale Converter for Wind Turbines

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***Abstract*— The wind power industry has enjoyed a strong and steady growth over the last decade, as the technological advances have made wind turbines bigger, reaching higher levels of capacity and efficiency. The latest generation of wind turbines has capacity up to 10MW [1], employing a full scale (100%) power electronics converter. The utilization of a full scale converter (FSC) in wind turbines design not only increases the efficiency of wind energy conversion, but also improves grid compatibility for high power wind turbines. The Full Scale Converter (FSC) with a Permanent Magnet Synchronous Generator (PMSG) configuration for wind turbine systems (WTS) requires less maintenance than other configurations, making the technology attractive for off-shore wind farms. In addition, the decreasing cost of power electronics devices and NdFeB magnets [2] are making this configuration more preferable in other kinds of applications such as off-grid rural areas and on-shore wind farms. This paper gives a review of FSC for PMSG-based wind turbines. The emerging technology is dominant in high power, off-shore applications and is very promising for other kinds of applications in the near future.**

***Index Terms*— Wind energy, Wind energy generation, Power conversion, AC-DC power converters.**

I. Introduction

THE Fifth Scientific Assessment on global climate by IPCC (the Intergovernmental Panel on Climate Change) concluded: *The earth doesn't stop warming, and humanity is the main cause for that*. The assessment goes thousands of pages, comprises prudently checked reports by hundreds of scientists around the world. Scientists agree that with the current burning rate of fossil fuels, the climate will soon comes to a critical point where we cannot turn back. On the other hand, with latest catastrophes happening around the world, like typhoon Haiyan or hurricane Katrina, with intensities at a record level in history further confirms the looming danger that scientists have anticipated [3]. Not only causing detrimental effect to our climate, fossil fuels also have limited resources and with the quick rise of the world's energy demand, they will sooner or later run out.

Renewable sources of energy, like wind energy, on the contrary, have many advantages over fossil fuels. The wind is abundant, and it doesn't seem to stop blowing at any time soon. Harnessing wind energy is a clean process and almost harmless to the environment. In the near future, electricity generated from the wind will have even lower levelized cost per MWh compared to electricity generated from coal or nuclear power [4]. However, a drawback of wind energy is its variability. The int[i]ermittent nature of the wind shrinks the capacity factor of wind farms to about 20% [5], [6], [7]. Recent technology in converter design together with the large-scale implementation of wind power plants (WPP) increases the capacity factor of wind farm substantially. Some new wind farms have capacity factor higher than 50% [5], [6], [7]. In the near future, new grid-scale energy storage technologies potentially can bring the capacity factor to even higher. For example, Ocean Renewable Energy Storage from MIT [3], Wind Hydrogen Storage Systems are very promising in this aspect. In addition, today's advanced technologies have made WPP perform as good as conventional fossil fuel or nuclear power plants in keeping the grid stable. Gigantic WPP nowadays can actively participate in grid voltage/frequency regulation on both primary and secondary control, eliminate all the anxiety about high wind energy penetration might make the grid become unstable. With these advantages, wind energy will be involved to be an important source of energy for the world, contribute to the solution for our climate and energy problems.

In recent years, technologists and companies have been trying to lower the cost of wind energy by increasing the output power, making wind turbine bigger and bigger (Fig. 1). Recently, the utilization of full scale power electronics converter in wind turbine system (WTS) has allowed a complete control of power conversion and optimization, increases wind turbine efficiency as well as reliability, allows WTS to meet the most stringent Grid Code (GC) requirements.

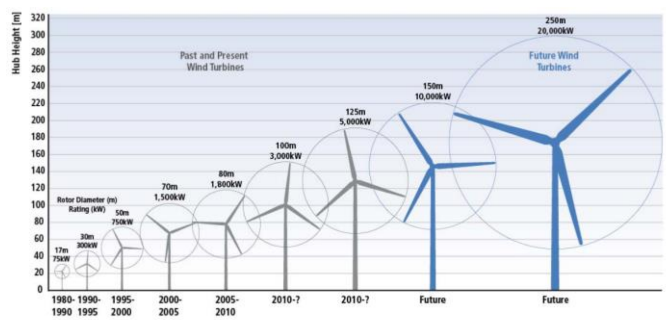

Fig. 1. The evolution of WTS. Source: IPCC (2011), "Special report on renewable energy"

Today's high level of renewable energy penetration has driven the need for "renewable generators" having the capability to provide active power control (APC) services, normally inherent in "traditional generators". These ancillary

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services feature in new Full Scale Converters (FSC) for WTS are crucial for grid reliability and lay the foundation for renewable energy to completely replace traditional sources of energy. The use of a Full Scale Converter in WTS seems to be the most successful configuration for the near future, winning the Doubly Fed Induction Generator (DFIG) actual market share [8].

This review studies about commercial Full Scale Converter for Permanent Magent Synchronous Generator WTS. The emerging technology has many advantages over other kinds of wind turbine including: higher efficiency, higher reliability, and especially future GC conformity. First, various configurations for wind energy conversion system are reviewed to give an overall picture of wind energy extraction process and point out where in the process we can do optimization. The discussion gives a quick look at old technologies and consider the advantages and drawbacks of each technologies. Second, the circuit design topology for FSC is reviewed. Finally, the most popular control technique for FSC is reviewed.

II. Overview of Wind Energy Conversion System

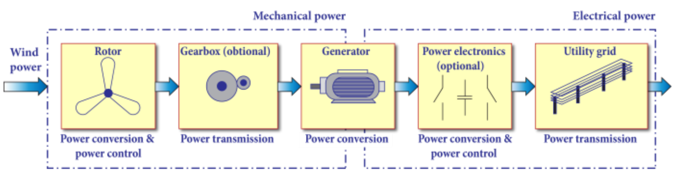

Fig. 2. Block diagram illustrates wind energy conversion process in a WTS [8].

In a modern WTS, wind energy is captured, adapted and exported into grid electricity following three steps (Fig. 2). First, kinetic energy of the wind is captured and converted by mechanical subsystem. The captured kinetic energy is then turned into electrical energy by electromechanical subsystem, which is the generator. Finally, the electrical subsystem adapts the energy and pushes into the grid. Apparently, there are three areas in a WTS that we need to control so that wind energy extraction is maximized and electricity transferring to the grid is stable and comply with GCs [8].

In the first stage, wind turbine's mechanical subsystem controls the yaw angle of the turbine following wind direction, in order to make the blades face the incoming wind as much as possible. Furthermore, depending on the speed of the incoming wind, tip-speed ratio is needed to be regulated to maximize power co-efficient, C_p, which is the ratio of the power extracted by the wind turbine relative to the energy available in the wind. By definition, tip-speed ratio (TSR) λ is the ratio of the speed of the blade, at its tip, to the speed of the wind. For example, if the tip of a blade is travelling at 120 mph and the wind speed is 20 mph, the TSR is 6. The fomular for TSR is [9]:

$$\lambda = \frac{\text{Speed at the tip of a blade}}{\text{Wind speed}} = \frac{\omega R}{v} \qquad (eq.\ 1)$$

For a specific wind turbine design, if the blades spin too slowly, then most of the wind will pass through the rotor without being captured by the blades. However, if the blades spin too fast, then the blades will always travel through used, turbulent wind. (There must be enough time lapses between two blades travelling through the same location so that new wind can enter and the next blade can harness the power from that new wind not the used, turbulent wind) [9]. For example Fig. 3, maximum power extraction from the wind occur at TSR = 6.

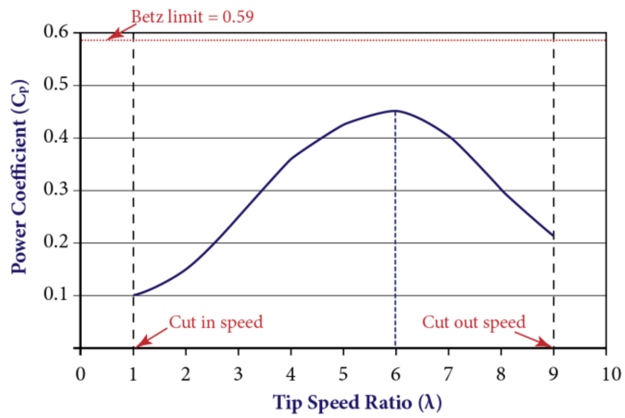

Fig. 3. Power coefficient as a function of TSR for a two-bladed rotor. [7].

There are various configuration for the second and third stages of energy conversion in wind turbines (Fig. 2). The first generation of grid-connected wind turbine, introduced in 1980s, is a simple fixed-speed squirrel-cage induction generator (Fig. 4) The generator is connected directly to grid electricity by a circuit breaker. The technology is simple and no control of electricity transferring to grid, other than just a simple Soft-Starter. In this configuration, rotor has to run at a fixed-speed and grid can see all the fluctuation, turbulence in wind energy captured at the blades.

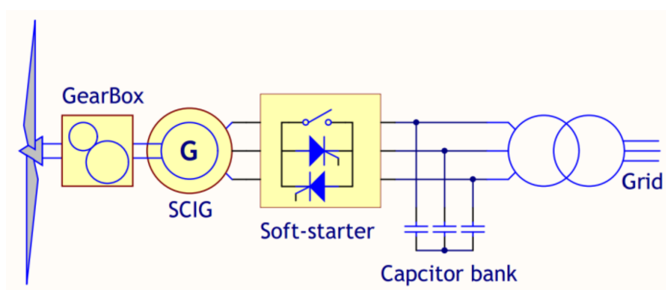

Fig. 4. Fixed-speed squirrel caged induction generator configuration [8].

The Doubly Fed Induction Generator (DFIG) was introduced in 1990s allowed more control of electricity transferring to the grid. This is a major step in wind turbine design which utilized power electronics to facilitate the need for more control and

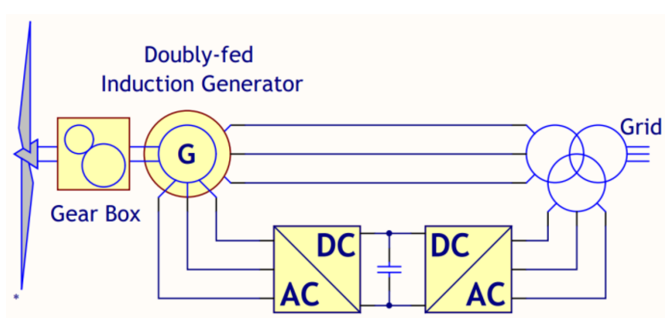

Fig. 5. Doubly Fed Induction Generator configuration with back-to-back power electronics converter connected to the rotor [8].

optimization of wind energy conversion as well as GCs conformity. In this configuration, there is a power electronics converter with rated power of 30% of the total system power (Fig. 5). This technology allow partial control of the reactive and active power injected into grid electricity. However, because the stator is directly coupled to the grid, even with the control of rotor field, some percentage of noises in the wind are still make it way into the grid. With an introduction of a chopper in the DC link of the converter, Fault-Ride-Through (FRT) capability could be archived in DFIG systems. However, maximum capacity that DFIG system could stay connected to the grid is limited during grid faults due to the direct connection of generator's stator to the grid which may produce over current. DFIG systems cannot scale to very big and high power. DFIG technology is more suitable for WTS with rated power less than 5MW [8].

In the early 2000s, Enercon and Siemens introduced the concept of full-scale converter (FSC) for Wind Turbine Systems, in which all power extracted from the wind is managed and transferred to utility grid by a power electronics converter (Fig. 6). This configuration allows a complete control and optimization of wind power conversion process. As a consequence, wind power extraction is optimized to the highest efficiency over the entire speed range, mechanical vibration is reduced to minimum. Maintainance cost is reduced dramatically. Traditional gearbox becomes optional because FSC allows wind turbine to work at a very low speed.

In addition, the complete decoupled of generator to the grid make it possible and more easily to implement advance control functions which may be required by future GCs when wind energy penetration is higher. Today's FSC-based WTS can actively participate in grid voltage/frequency regulation on both primary and secondary control. They have a full rolling capacity to support grid recovering when there are faults or to stabilize the grid when there are disturbances [8]. The drawback of FSC PMSG-based WTS is the higher cost of power electronics converter and permanent magnet inside the generator. However, with the decreasing cost trending of rare earth metals (which used to make NdFeB magnets) [1] and power electronics devices, FSC PMSG-based WTS are becoming more and more popular in all types of wind power applications. Currently, the main applications of FSC PMSG-based WTS are large-scale high power and off-shore wind turbines. These WTS has power rating over 2MW.

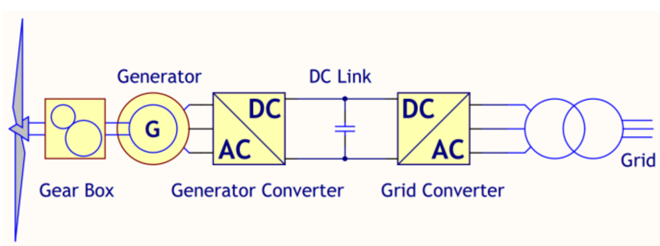

Fig. 6. Full-Scale back-to-back converter configuration [8].

III. Design Topologies of Full Scale Converter in Synchronous Wind Generator

Fig. 6 discloses a typical block diagram of FSC design. It's depending on application requirements that system designers will have to chose the best topology for converter design. For example, some topologies are suitable for Medium Voltage, High Power applications, offering redundancy to increase system's reliability which required in off-shore wind turbines, while others are great for low cost, micro-grid applications in rural areas. Generally, the design of FSC in WTS employ two converters (Fig. 6). Topologies for converters can be categorized as [10]:

- Two level converters.
- Multilevel converters.
- Tandem converters.
- Matrix converters.
- Resonant converters.

A full discussion about each topologies, their working principles, pros and cons is beyond the scope of this paper. This section offers an overview of the most common topologies and discuss the advantages and drawbacks innate in each type of circuit design. The discussion focus on Voltage Source Converter (VSC). Current Source Converter (CSC) and Z-Source Converter (ZSC) are not discussed. Although CSC and ZSC are very promising technologies for High Power, Medium Voltage WTS, a lot of work need to put into R&D to make these types of converters practicable for commercial applications. VSC is still the dominant technology in converter applications for WTS [11].

A. *Converters using Diode Bridge as AC/DC.*

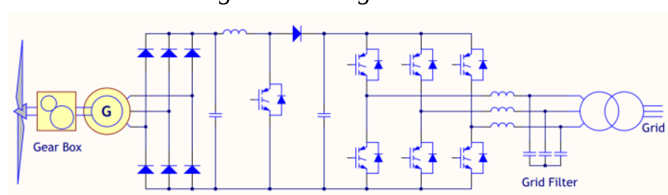

Fig. 7. FSC-based Synchronous WTS with Diode Rectifier [15].

The simplest type of FSC uses a diode bridge rectifier to convert AC output from a generator to DC. The diode bridge can either be a popular 6-pulses rectifier or a 12-pulses rectifier to reduce input current harmonic. The DC voltage is then boost to an appropriate level, normally by a simple single channel DC/DC boost converter for low cost and low power (Fig. 7). For higher power, two or three channel interleaved (phase shift) boost converter may be used instead. The DC/DC booster main functions are: boost the DC voltage, keep the DC link voltage stable and perform Maximum Power Point Tracking (MPPT). The grid side DC/AC converter is normally a two level voltage source inverter which convert DC to AC. The main drawback of this topology is high torque ripple resulting from high current harmonic from the diode bridge rectifier. High torque ripple is harmful for wind turbine's mechanical systems, especially if the turbine is big. However, the advantages are low cost and simple control. This design topology is suitable for low- and medium-power WTS from a few kilowatts to 1MW.

B. Two-Level Back-To-Back Voltage-Source Converters

This most popular topology comprises two Voltage Source Inverter (VSI) connected to each other at its back (DC side) [10]. Fig. 8 shows a simplified circuit and block diagram for this configuration. Each VSI composed of six switching semiconductor devices which could be MOSFET, IGBT or IGCT. Each VSI has a DC side and a 3-phases AC side. The VSI is very flexible in that power flow in each VSI is bidirectional, meaning we can control the power to flow from AC side to DC side or vice versa. The generator side VSI often control the real power flow and do maximum power point tracking (MPPT), while the grid-side VSI often control the reactive power supply to the grid and keep the DC link voltage at constant. Filtering is required in AC side of both VSI. The dynamic control of VSI is depended on the time constant of the filter. Designing of filter is a trade-off between high filtering (low harmonic output) and fast dynamic response [8].

VSI is the most popular topology used in industry, mainly for motor control. As a result, the knowledge and documentation about this type of inverter is very extensive and well established. Also, there are low cost, standard components specificly designed for this type of inverter which help reduce manufacturing cost. The main drawback for this type of converter is high switching loss. Since there are two inverters with all switching components work under hard switching condition. Other drawback are: big DC link capacitor, higher harmonic in output voltage and current, higher voltage change rate (dv/dt). This topology is suitable for WTS with power rating up to 2MW [10].

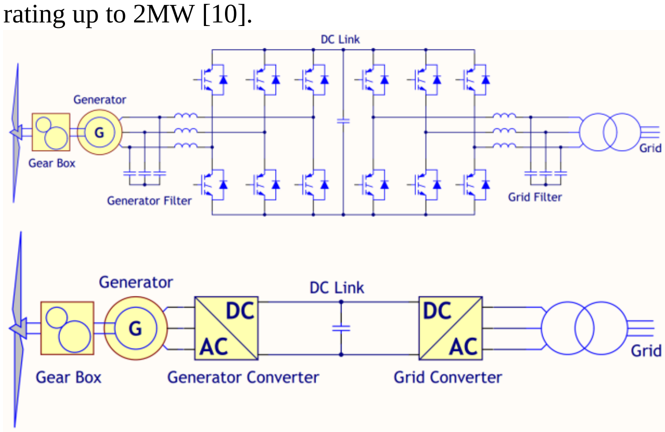

Fig. 8. Two-Level Back-To-Back Voltage-Source Converters [8].

C. Three-Level Back-To-Back Neutral Point Clamped and Multi-Level Converters

When power level increases to over 2MW, a multi-level converter is preferable for both economic and technical reasons. Fig. 9 shows a simplified circuit for Thee-Level Back-to-Back Neutral Point Clamped (NPC) Converter. This configuration is similar with the previous topology except that the normal two levels VSI is replaced with three-level NPC VSI. The main idea behind multi-level converter is to create a sinusoidal high voltage output from several levels of voltage [10]. In this way multi-level converter will has lower voltage change rate (dv/dt), lower blocking voltage in each switching device, lower switching loss, lower harmonic distortion, lower leakage current and EMI. The main drawbacks are this design topology requires more switching components (means higher cost), complexity in design and control, high conducting loss.

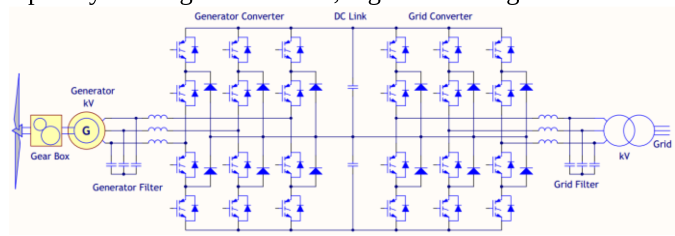

Fig. 9. Three-Level Back-To-Back Neutral Point Clamped Converters [8].

D. Multi-Cell Low Voltage (LV) Converters

Multi-Cell Low Voltage topologies combines VSI, either two-level or multi-level, to archive high current output. Also the interleaved (phase shift) modulation on the grid side inverter of these topologies help reduce harmonic distortion. Fig. 10 and Fig. 11 are two examples of Multi-Cell Low Voltage Converter (less than 1kV).

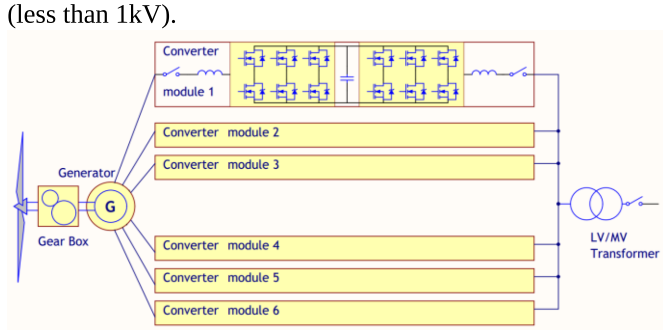

Fig. 10. Back-to-back converters fed by a six-phase generator. Parallel connected in generator side and interleaved on the grid side [8].

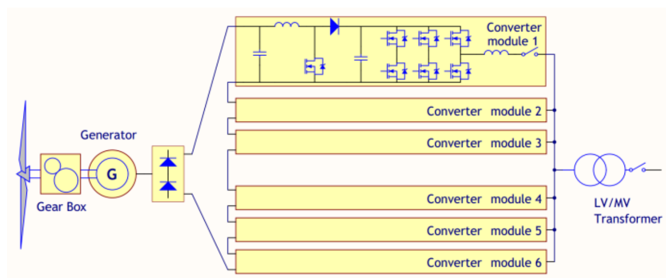

Fig. 11. N-leg diode bridge fed by a synchronous generator producing a high DC voltage shared among several grid/converters connected in serial on generator side and interleaved on the grid side [8].

E. Other topologies for Medium Voltage (MV) converters

Typically, in a low voltage 690V/2MW WTS, there is a phase current of 1700A power transmitted from a nacelle (which is a chamber at the top of a wind tower, can be as high as 100 ft. in the air) to the ground. This requires a parallel connection of multiple cables per phase and a considerable voltage drop and conductor loss in the transmission line. The drawback can be mitigated by employing a transformer in the nacelle to increase the voltage before transmission. However, the structure backing the nacelle weight introduces extremely higher costs [12]. Issued US Patent 8129853 discloses a transformerless converter topology in harmony with generator to produce a high voltage output, which then can be transmitted to the tower bottom efficiently.

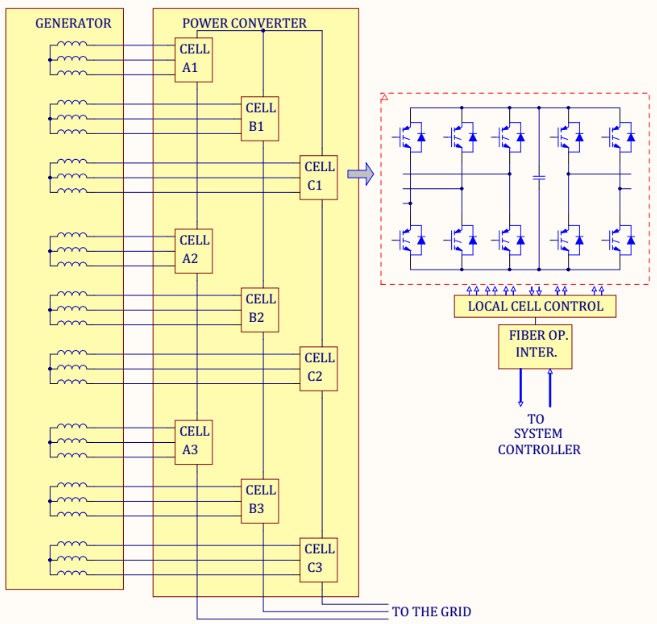

Fig. 12. A high-voltage inverter including series-connected chopper/dump load circuits in the DC-link [12].

The general concept of the invention involves cascading of power stages to create high voltage output from multiple isolated low voltage power supplies. To be able to do cascading of power stages, the invention requires multiple isolated power supplies from Wind Turbines to feed directly into each power stage. Each power stage may receive at least one of the isolated power supplies. In an embodiment of the invention, each power stage is a single phase full-bridge converter. By serial cascading of power stages we can built a high voltage converter efficiently from low voltage semiconductor devices. The idea to create sinusoidal high voltage output is similar to that of Multi-level converter: creating a sinusoidal high voltage output from several levels of voltage [10]. Fig. 12 shows a typical setup for this topology.

The great unique advantage of this topology is the modular nature in design which allow redundancy to improve overall system reliability. Other advantages and drawback of this topology are similar to multi-cell converter: lower harmonic distortion, lower switching loss, lower voltage change rate (dv/dt), smaller filter elements, lower cost, lower leakage current and EMI, etc. The disadvantages are high conducting loss, complicated wiring and control.

Patent application publication US 20130181532 discloses a different approach for removing the traditional step-up transformer. The basic idea was also serially connecting low voltage switching units so that together they can work under high voltage. However, connecting switching devices in series is known to be a difficult task due to voltage balancing problems arising from different switching times of the switching devices. If the voltage across serial connected switching devices are not properly balanced, overvoltage levels typically ends up on a particular switching devices [13] and create damage to the whole system. So the patent further discloses circuit to balance voltage between serially connected switching units (Fig. 13).

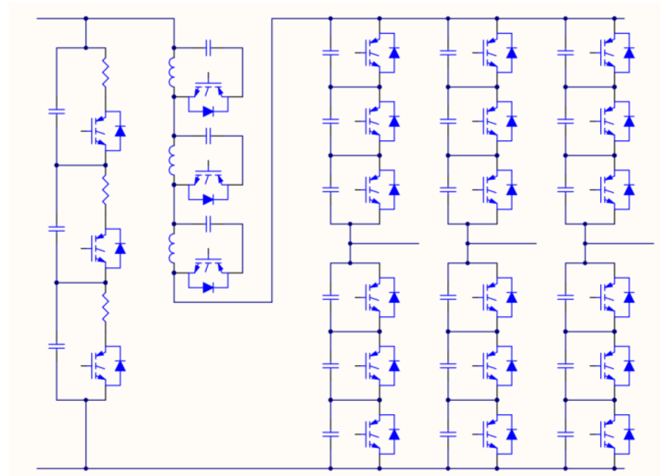

Fig. 13. A high-voltage inverter including series-connected chopper/dump load circuits in the DC-link [13]

IV. FSC Based Wind Turbine Control

Control system in a modern Wind Turbine involves in both slow and fast control dynamic [8]. The mechanical subsystem, slow control dynamic, is responsible for controlling the yaw angle to face current wind direction, and changing pitch angle of the blades to limit picking up wind when the wind is too fast and turbine reach nominal power. The electrical subsystem, fast control dynamic, is responsible for controlling active/reactive power transferring to the grid following command from wind farm's supervisor which, in turn, received command from Transmission System Operators (TSO) (Fig. 14). The electrical subsystem also performs maximum power point tracking (MPPT) and overload protection.

As mandatory by new GCs, high power WTS are required to support grid stability as good as conventional generators do. These functions including: inertia response, primary control (also called primary frequency response or governor droop), secondary control (or automatic generation control) and fault ride-through (FRT). Inertia response is the immediate response of conventional synchronous generator which has a big inertia rotating at a high speed. When a load is connected, the prime mover dynamo will immediately response by increase the amperage. It is not easy to decrease its speed, because of the big inertia of the rotor. However, the inertia response isn't last long. The rotating speed will decrease which cause the grid frequency to decrease. (If the load is disconnected, the reversed will happens, i.e. increasing frequency. So it is said that frequency

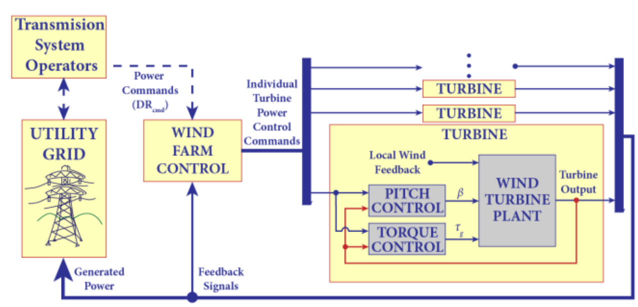

Fig. 14. the interconnection between the utility grid, the TSO (or grid operator), the wind farm controller, and the individual turbine. [14]

reflects the balance between load and supply in a grid.) When there is a decrease in frequency, the conventional synchronous generator have a response, called primary control, by increasing the power (i.e. put more fuel) to try to bring the frequency back to set point. The primary control typically responses within 12s to 14s [16]. This is the automatic feedback by individual units. The secondary control involves coordination across many units in a wide area on a slow time scale to make sure that frequency and exchange energy schedules between regions are kept to set points [15].

Renewable energy sources are said to "lack natural inertia". Wind and solar are not something that we can control like putting more "fossil fuel". Controlling of wind generator to behave as good as conventional generator without compromising for less energy harvested or higher cost with added battery is one of the hard topics that keeping researchers from universities around the world busy. Beside that, control of converter under grid faults is also a huge and difficult topic. A full discussion about all the control topics of FSC for Synchronous Wind Turbine Generator is beyond the scope of this paper. This section provides an overview of a most popular control technique: Field Oriented Control (FOC), which applied for back-to-back voltage source converter topology in Fig. 8 and Fig. 9. FOC control applies to both generator side converter and grid side converter.

A. Control of generator side converter

Unless there is a command from Wind Farm Supervisor to decrease the output power of WTS, the generator side converter's duty is controlling the generator in order to pull maximum of active power out of the wind and push into the DC link (Fig. 8). First, Wind Turbine measures wind speed to decide the optimal torque T_{mppt} that generator should have to maximize power captured from the wind (maximum power

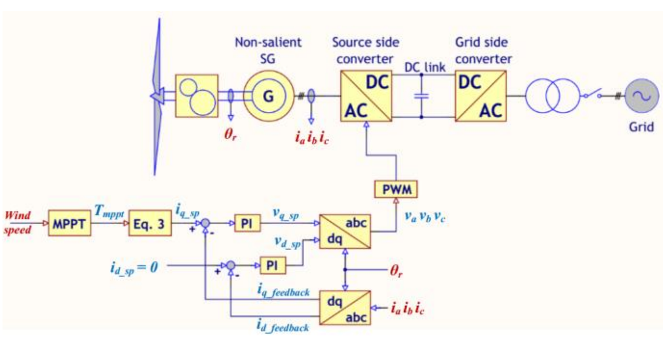

Fig. 15. Control System block diagram for a Full Scale Conveter with ZDC control [17].

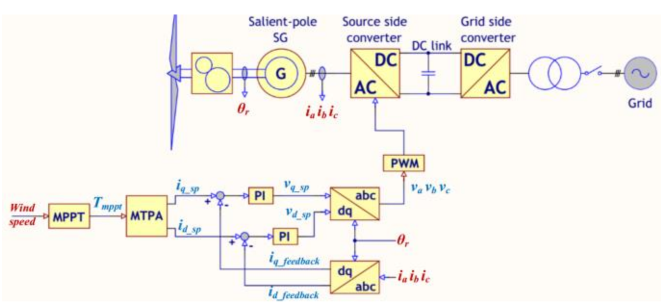

Fig. 16. Control System block diagram for Full Scale Conveter with MPTA control [17].

point tracking). Then the generator side converter control the generator to have the output torque equal T_{mppt}. According to [18], the electromagnetic torque output T_e of the generator expressed in dq synchronous reference frame of the stator currents is given as:

$$T_e = \frac{3p}{2}\left[\psi_{PM} i_q + i_d i_q \left(L_d - L_q\right)\right] \qquad (eq.2)$$

Where L_d, L_q, i_d and i_q are the d- and q- axis synchronous inductances and current of stator. Ψ_{PM} is the permanent magnet flux of rotor. The first component of total torque, is proportional to stator current component i_q , called: "magnet" torque. The second component, involves both i_d and i_q , called reluctance torque [18].

For Nonsalient generator, because $L_d = L_q$, The d- component of stator current, i_d doesn't contribute to the output torque T_e, only the q- component of stator current i_q contributes to output torque T_e. So we let i_d to zero to minimize loss, and try to control i_q to output the required torque $T_e = T_{mppt}$ (eq. 3). The control technique is called: Zero d-Axis Current (ZDC) control [17] (Fig. 15). An intuitive way to think about ZDC control is we're trying to make the stator flux always perpendicular to the rotor flux. Because only the quadrature component of stator flux create torque, the direct component only create heat.

$$i_q = \frac{2T_e}{3p\psi_{PM}} = \frac{2T_{mppt}}{3p\psi_{PM}} \qquad (eq.\ 3)$$

For Salient-pole generator, $L_d < L_q$ is an important property. Although we can apply ZDC control technique with Salient-pole generator (because $i_d = 0$, only i_q contributes to torque!), the technique cannot reach full dynamic range and fast dynamic response [18]. The main reason is there are always errors in sensors reading, calculations and the response of PI control loop is not instantaneous. So there is always some instance i_d doesn't equal zero. When i_d not equal zero, the ZDC method is not valid anymore. ZDC neglected an important property of salient-pole generator, which is the reluctance torque, in the total output torque calculation T_e. The best control technique for Salient-pole generator called: Maximum Torque Per Ampere (MTPA) (Fig. 16). The MTPA control guarantees reluctance torque is used in output calculation of required torque T_e .

The different between ZDC and MTPA is in how the set-point for stator current (i_d and i_q) is obtained. In ZDC, set-point for i_d simply set to zero and set-point for i_q is calculated from the optimum torque T_{mppt}. In MTPA, there are many techniques to get optimum set-point (i_d, i_q): [19] and [20] used a lookup table, [21] and [22] discussed a simplified methods and a complicated method using fuzzy-logic control with neural networks. By controlling stator current (i_d, i_q), both methods try to control the output torque T_e of the generator to follow the optimum torque T_{mppt} (obtained by MPPT algorithm) so that maximum wind power is captured.

B. Control of grid side converter

The control of grid side converter is based on the instantaneous power theory for 3 phase systems, which define active power (P) and reactive power (Q) in an arbitrary synchronous dq reference frame [24]:

$$P = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \qquad (eq.3)$$

$$Q = \frac{3}{2}\left(v_q i_d - v_d i_q\right) \qquad (eq.4)$$

For a particular dq reference frame that has the d axis aligned with grid voltage phasor $\boldsymbol{v}$, we have:

$$P = \frac{3}{2} v_d i_d \qquad (eq.5)$$

$$Q = -\frac{3}{2} v_d i_q \qquad (eq.6)$$

From the above equation, we can control the active power by controlling i_d, and control the reactive power by controlling i_q. Generally, i_d and i_q are fixed targets which we can easily be controlled by a PI loop. Fig. 17 shows a block diagram for controlling active and reactive power based on the synchronous dq frame.

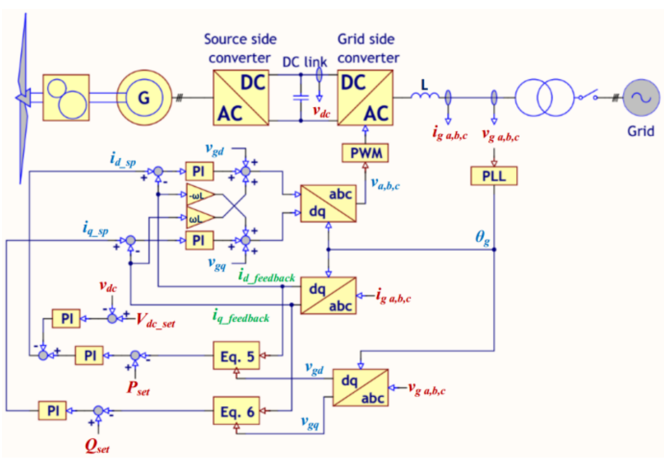

Fig. 17. PQ closed-loop voltage oriented control based on the synchronous dq frame [23]

V. Conclusion

Similar to many other systems, wind turbine systems have various configurations suitable for different types of applications. Because real world's wind power applications vary significantly in terms of requirement, budget, wind condition, etc. There is no single best configuration for all types of applications. It depends on each particular situation that system designer may choose the best wind turbine configuration for deployment. For rural areas off-grid applications, FSC with PMSG configurations are more preferable, because DFIG wind turbines can not operate in an off-grid condition. For most of the on-shore wind farms, which are easier to do maintenance than off-shore, the preferable choices are low cost DFIG wind turbines. For some on-shore wind farms where wind condition may change from very low speeds to very high speeds, FSC wind turbines may be chosen for maximum wind energy capture on the entire speed range. For off-shore and high-power wind farms, FSC are the dominant configurations due to higher reliability and better GC conformity.

FSC technology improves reliability, efficiency, as well as GC conformity compared to older technologies. However, the primary drawback is the up-front cost, which is the cost for building the generation unit. For that reason, DFIG is still the most popular configuration on the market at the moment. In the near future, semiconductor switching device will be reduced in cost and increased in performance according to Moore's law; wind turbines will grow bigger. It is very likely that FSC will become the most popular configuration for WTS.

Reduction in cost, increasing in reliability are always the main drivers for wind turbine development. The evolution of modern wind turbines is an impressive story involves scientific, engineering along with strong entrepreneurial spirit. The story is far from finished. Many technical and economic challenges are waiting to be solved; more impressive achievements will come [25].

Nomenclature

WTS	Wind Turbines Systems
FSC	Full Scale Converter
SG	Synchronous Generator
PMSG	Permanent Magnet Synchronous Generator
GC	Grid Code
MPPT	Maximum Power Point Tracking
VSI	Voltage Source Inverter
FOC	Field Oriented Control
ZDC	Zero d-axis Current
MTPA	Maximum Torque per Ampere

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