CONSTANT POWER CONTROL OF DFIG WIND TURBINES WITH SUPERCAPACITOR ENERGY STORAGE

Abstract:The increasing penetration of wind power into electric power grids, energy storage devices will be required to dynamically match the intermittency of wind energy.This project proposes a novel two-layer constant power control scheme for a wind farm equipped with doubly fed induction generator (DFIG) wind turbines. Each DFIG wind turbine is equipped with a super capacitor energy storage system (ESS) and is controlled by the low-layer wind turbine generator (WTG) controllers and coordinated by a high-layer wind farm supervisory controller (WFSC). To enable WTGs to effectively participate in frequency and active power regulation, unit commitment, economic dispatch, and electricity market operation, energy storage devices will be required to dynamically match the intermittency of wind energy. The WFSC generates the active power references for the low-layer WTG controllers according to the active power demand from or generation commitment to the grid operator; the low-layer WTG controllers then regulate each DFIG wind turbine to generate the desired amount of active power, where the deviations between the available wind energy input and desired active power output are compensated by the ESS. Simulation studies are carried out in MATLAB/SIMULATION on a wind farm equipped with 15 DFIG wind turbines to verify the effectiveness of the proposed control scheme.

1. INTRODUCTION

1.1 WIND TURBINE

Generators (WTGs) are usually controlled to generate maximum electrical power from wind under normal wind conditions. However, because of the variations of the wind speed, the generated electrical power of a WTG is usually fluctuated. Currently, wind energy only provides about 1%–2% of the U.S.'s electricity supply. At such a penetration level, it is not necessary to require WTGs to participate in automatic generation control, unit commitment, or frequency regulation.However, it is reasonable to expect that wind power will be capable of becoming a major contributor to the nation's and world's electricity supply over the next three decades. For instance, the European Wind Energy Association has set a target to satisfy more than 22% of European electricity demand with wind power by 2030. In the U.S., according to a report by the Department of Energy, it is feasible to supply 20% of the nation's electricity from wind by 2030. At such high levels of penetration, it will become necessary to require WTGs to supply a desired amount of active power to participate in automatic generation control or frequency regulation of the grid. Moreover, to optimize the economic performance of power systems with high penetrations of wind power, it would be desired to require WTGs to participate in unit commitment, economic dispatch, or electricity market operation. In practice, short-term wind power prediction is carried out to help WTGs provide these functions. However, even using the state-of-the-art methods, prediction errors are present. Under these conditions, the replacement power is supported by reserves, which, however, can be more expensive than base electricity prices. To enable WTGs to effectively participate in frequency and active power regulation, unit commitment, economic dispatch, and electricity market operation, energy storage devices will be required to dynamically match the intermittency of wind energy.

1.2 WIND POWER

Wind is abundant almost in any part of the world. Its existence in nature caused by uneven heating on the surface of the earth as well as the earth's rotation means that the wind resources will always be available. The conventional ways of generating electricity using non renewable resources such as coal, natural gas, oil and so on, have great impacts on the environment as it contributes vast quantities of carbon dioxide to the earth's atmosphere which in turn will cause the temperature of the earth's surface to increase, known as the green house effect.

Hence, with the advances in science and technology, ways of generating electricity using renewable energy resources such as the wind are developed. Nowadays, the cost of wind power that is connected to the grid is as cheap as the cost of generating electricity using coal and oil. Thus, the increasing popularity of green electricity means the demand of electricity produced by using non renewable energy is also increased accordingly.

1.3 FEATURES OF WIND POWER SYSTEMS:

There are some distinctive energy end use features of wind power systems

Most wind power sites are in remote rural, island or marine areas. Energy requirements in such places are distinctive and do not require the high electrical power.

I. A power system with mixed quality supplies can be a good match with total energy end use i.e. the supply of cheap variable voltage power for heating and expensive fixed voltage electricity for lights and motors.

II. Rural grid systems are likely to be weak (low voltage 33 KV). Interfacing a Wind Energy Conversion System (WECS) in weak grids is difficult and detrimental to the workers' safety.

III. There are always periods without wind. Thus, WECS must be linked energy storage or parallel generating system if supplies are to be maintained.

1.4 POWER FROM THE WIND:

Kinetic energy from the wind is used to turn the generator inside the wind turbine to produced electricity. There are several factors that contribute to the efficiency of the wind turbine in extracting the power from the wind. Firstly, the wind speed is one of the important factors in determining how much power can be extracted from the wind. This is because the power produced from the wind turbine is a function of the cubed of the wind speed. Thus, the wind speed if doubled, the power produced will be increased by eight times the original power. Then, location of the wind farm plays an important role in order for the wind turbine to extract the most available power form the wind.

The next important factor of the wind turbine is the rotor blade. The rotor blades length of the wind turbine is one of the important aspects of the wind turbine since the power produced from the wind is also proportional to the swept area of the rotor blades i.e. the square of the diameter of the swept area.

Hence, by doubling the diameter of the swept area, the power produced will be fourfold increased. It is required for the rotor blades to be strong and light and durable.

As the blade length increases, these qualities of the rotor blades become more elusive. But with the recent advances in fiberglass and carbon-fiber technology, the production of lightweight and strong rotor blades between 20 to 30 meters long is possible. Wind turbines with the size of these rotor blades are capable to produce up to 1 megawatt of power.

The relationship between the powers produced by the wind source and the velocity of the wind and the rotor blades swept diameter is shown below.

$$P_{wind} = \frac{\pi}{8} dD^2 v_{wind}^3$$

The derivation to this formula can be looked up in [2]. It should be noted that some books derived the formula in terms of the swept area of the rotor blades (A) and the air density is denoted as δ□.

Thus, in selecting wind turbine available in the market, the best and efficient wind turbine is the one that can make the best use of the available kinetic energy of the wind.

Wind power has the following advantages over the traditional power plants.

- Improving price competitiveness,
- Modular installation,
- Rapid construction,
- Complementary generation,
- Improved system reliability, and
- Non-polluting.
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1.5 WIND TURBINES:

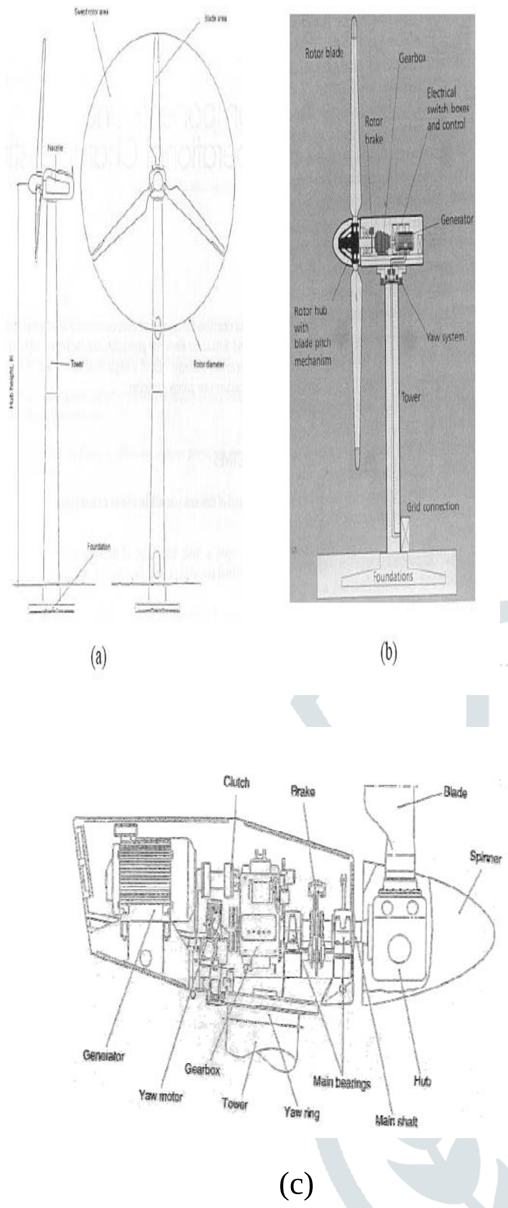
There are two types of wind turbine in relation to their rotor settings. They are:

- Horizontal-axis rotors, and
- Vertical-axis rotors.

In this report, only the horizontal-axis wind turbine will be discussed since the modeling of the wind driven electric generator is assumed to have the horizontal-axis rotor.

The horizontal-axis wind turbine is designed so that the blades rotate in front of the tower with respect to the wind direction i.e. the axis of rotation are parallel to the wind direction. These are generally referred to as upwind rotors. Another type of horizontal axis wind turbine is called downwind rotors which has blades rotating in back of the tower. Nowadays, only the upwind rotors are used in large-scale power generation and in this report, the term .horizontal-axis wind turbine refers to the upwind rotor arrangement.

The main components of a wind turbine for electricity generation are the rotor, the transmission system, and the generator, and the yaw and control system. The following figures show the general layout of a typical horizontal-axis wind turbine, different parts of the typical grid-connected wind turbine, and cross-section view of a nacelle of a wind turbine.It is reasonable to expect that wind power will be capable of becoming a major contributor to the nation's and world's electricity supply over the next three decades This is because the power produced from the wind turbine is a function of the cubed of the wind speed. Thus, the wind speed if doubled, the power produced will be increased by eight times the original power. Then, location of the wind farm plays an important role in order for the wind turbine to extract the most available power form the wind.



Figs1.2: (a) Main Components of Horizontal-axis Wind Turbine
(b) Cross-section of a Typical Grid-connected Wind Turbine
(c) Cross-section of a Nacelle in A Grid-connected Wind Turbine

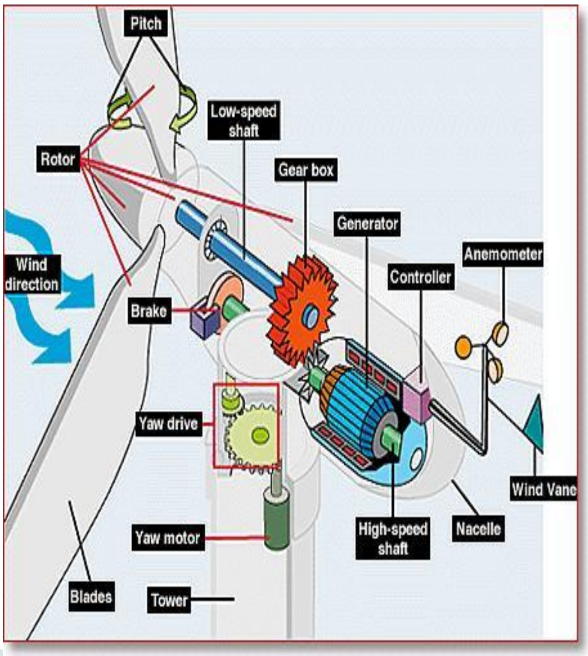


FIG:1.3 The main components of a wind turbine can be classified as i) Tower ii) Rotor system
iii) Generator iv) Yaw v) Control system and vi) Braking and transmission system

(I) TOWER:

It is the most expensive element of the wind turbine system. The lattice or tubular types of towers are constructed with steel or concrete. Cheaper and smaller towers may be supported by guy wires. The major components such as rotor brake, gearbox, electrical switch boxes, controller, and generator are fixed on to or inside nacelle, which can rotate or yaw according to wind direction, are mounted on the tower. The tower should be designed to withstand gravity and wind loads. The tower has to be supported on a strong foundation in the ground. The design should consider the resonant frequencies of the tower do not coincide with induced frequencies from the rotor and methods to damp out if any. If the natural frequency of the tower lies above the blade passing frequency, it is called *stiff* tower and if below is called *soft* tower.

(II) ROTOR:

The aerodynamic forces acting on a wind turbine rotor is explained by aerofoil theory. When the aerofoil moves in a flow, a pressure distribution is established around the symmetric aerofoil shown in Fig (a).

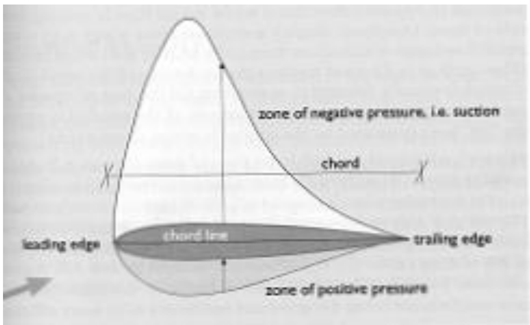


Fig 1.4 zons of low and high pressure

A reference line from which measurements are made on an aerofoil section is referred to as chord line and the length is known as chord. The angle, which an aerofoil makes with the direction of airflow measured against the chord line is called the angle of attack.

The generation of lift force L on an aerofoil placed at an angle of attack α to an oncoming flow is a consequence of the distortion of the streamlines of the fluid passing above and below the aerofoil. When a blade is subjected to unperturbed wind flow, the pressure decreases towards the center of curvature of a streamline.

The consequence is the reduction of pressure (suction) on the upper surface of the aerofoil compared to ambient pressure, while on the lower side the pressure is positive or greater. The pressure difference results in lift force responsible for rotation of the blades.

These forces are both proportional to the energy in the wind. To attain a high efficiency of rotor in wind turbine design is for the blade to have a relatively high lift-to-drag ratio. This ratio can be varied along the length of the blade to optimize the turbine's energy output at various wind speeds. The lift force, drag force or both extract the energy from wind. For aerofoil to be aerodynamically efficient, the lift force can be 30 times greater than the drag force.

Cambered or asymmetrical aerofoils have curved chord lines. The chord line is now defined as the straight line joining the ends of the camber line and α is measured from this chord line. Cambered aerofoil is preferred to symmetrical aerofoil because they have higher lift/drag ratio for positive angles of attack. It is observed that the lift at zero angle of attack is no longer zero and that the zero lift occurs at a small negative angle of attack of approximately 4^{o}. The center of pressure, which is at the ¼ chord position on symmetrical aerofoil has at the ¼ chord position on cambered aerofoil and moves towards the trailing edge with increasing angle of attack.

Arching or cambering a flat plate will cause it to induce higher lift force for a given angle of attack and blades with a cambered plate profile work well, under the conditions experienced by high solidity, multi bladed wind turbines. For low solidity turbines, the use of aerofoil section is more effective.

The characteristics of an aerofoil, the angle of attack, the magnitude of the relative wind speed are the prime parameters responsible for the lift and drag forces. These forces acting on the blades of a wind turbine rotor are transformed into a rotational torque and axial thrust force. The useful work is produced by the torque where as the thrust will overturn the turbine. This axial thrust should be resisted by the tower and foundations.

1.6 ROTOR SPEED:

Low speed and high-speed propeller are the two types of rotors. A large design tip speed ratio would require a long, slender blade having high aspect ratio. A low design tip speed would require a short, flat blade.

The low speed rotor runs with high torque and the high-speed rotor runs with low torque. The wind energy converters of the same size have essentially the same power output, as the power output depends on rotor area. The low speed rotor has curved metal plates. The number of blades, weight, and difficulty of balancing the blades makes the rotors to be typically small. They get self-started because of their aerodynamic characteristics.

The propeller type rotor comprises of a few narrow blades with more sophisticated airfoil section. When not working, the blades are completely stalled and the rotor cannot be self-started. Therefore, propeller type rotors should be started either by changing the blade pitch or by turning the rotor with the aid of an external power source (such as generator used as a motor to turn the rotor). Rotor is allowed to run at variable speed or constrained to operate at a constant speed. When operated at variable speed, the tip speed ratio remains constant and aerodynamic efficiency is increased.

1.7 ROTOR ALIGNMENT:

The alignment of turbine blades with the direction of wind is made by upwind or downwind rotors. Upwind rotors face the wind in front of the vertical tower and have the advantage of somewhat avoiding the wind shade effect from the presence of the tower. Upwind rotors need a yaw mechanism to keep the rotor axis aligned with the direction of the wind. Downwind rotors are placed on the lee side of the tower. A great disadvantage in this design is the fluctuations in the wind power due to the rotor passing through the wind shade of the tower which gives rise to more fatigue loads.

Downwind rotors can be built without a yaw mechanism, if the rotor and nacelle can be designed in such a way that the nacelle will follow the wind passively.

This may however include gyroscopic loads and hamper the possibility of unwinding the cables when the rotor has been yawing passively in the same direction for a long time, thereby causing the power cables to twist.

Upwind rotors need to be rather inflexible to keep the rotor blades clear of the tower, downwind rotors can be made more flexible. The latter implies possible savings with respect to weight and may contribute to reducing the loads on the tower. The vast majority of wind turbines in operation today have upwind rotors.

1.8 NUMBER OF ROTOR BLADES:

The three bladed rotors are the most common in modern aero generators. Compared to three bladed concepts, the two and one bladed concepts have the advantage of representing a possible saving in relation to cost and weight of the rotor. However, the use of fewer rotor blades implies that a higher rotational speed or a larger chord is needed to yield the same energy output as a three bladed turbine of a similar size. The use of one or two blades will also result in more fluctuating loads because of the variation of the inertia, depending on the blades being in horizontal or vertical position and on the variation of wind speed when the blade is pointing upward or downward.

Therefore, the two and one bladed concepts usually have so-called teetering hubs, implying that they have the rotor hinged to the main shaft. This design allows the rotor to teeter in order to eliminate some of the unbalanced loads. One bladed wind turbines are less widespread than two–bladed turbines. This is because they in addition to a higher rotational speed, more noise and visual intrusion problems, need a counter weight to balance the rotor blade.

(IV)GENERATOR:

Electricity is an excellent energy vector to transmit the high quality mechanical power of a wind turbine. Generator is usually 95% efficient and transmission losses should be less than 10%. The frequency and voltage of transmission need not be standardized, since the end use requirements vary. There are already many designs of wind/ electricity systems including a wide range of generators.

The distinctive features of wind/electricity generating systems are:

Wind turbine efficiency is greatest if rotational frequency varies to maintain constant tip speed ratio, yet electricity generation is most efficient at constant or near constant frequency.

i) Mechanical control of turbine to maintain constant frequency increases complexity and expense. An alternative method, usually cheaper and more efficient is to vary the electrical load on the turbine to control the rotational frequency.

ii) The optimum rotational frequency of a turbine in a particular wind speed decreases with increase in radius in order to maintain constant tip speed ratio. Thus, only small turbines of less than 2 m radius can be coupled directly to generators. Larger machines require a gearbox to increase the generator drive frequency.

iii) Gearboxes are relatively expensive and heavy. They require maintenance and can be noisy. To overcome this problem, generators with a large number of poles are being manufactured to operate at lower frequency.

iv) The turbine can be coupled with the generator to provide an indirect drive through a mechanical accumulator (weight lifted by hydraulic pressure) or chemical storage (battery). Thus, generator control is independent of turbine operation.

The generators used with wind machines are i) Synchronous AC generator ii) Induction AC generator and iii) Variable speed generator

1.9 SYNCHRONOUS AC GENERATOR:

The Synchronous speed will be in the range of 1500 rpm – 4 pole, 1000 rpm – 6 pole or 750 rpm, - 8 pole for connection to a 50 Hz net work. The ingress of moisture is to be avoided by providing suitable protection of the generator. Air borne noise is reduced by using liquid cooling in some wind turbines. An increase of the damping in the wind turbine drive train at the expense of losses in the rotor can be obtained by high slip at rated power output.

Synchronous generators run at a fixed or synchronous speed, N_s. We have $N_s = 120 f/p$, where p is the number of poles, f is the electrical frequency and N_s is the speed in rpm.

1.10 INDUCTION AC GENERATOR:

They are identical to conventional industrial induction motors and are used on constant speed wind turbines. The torque is applied to or removed from the shaft if the rotor speed is above or below synchronous. The power flow direction in wires is the factor to be considered to differentiate between a synchronous generator and induction motor. Some design modifications are to be incorporated for induction generators considering the different operating regime of wind turbines and the need for high efficiency at part load, etc.

1.11 VARIABLE SPEED GENERATOR:

Electrical variable speed operation can be approached as:

- All the output power of the wind turbine may be passed through the frequency converters to give a broad range of variable speed operation.
- A restricted speed range may be achieved by converting only a fraction of the output power.

(V)YAW SYSTEM:

It turns the nacelle according to the actuator engaging on a gear ring at the top of the tower. Yaw control is the arrangement in which the entire rotor is rotated horizontally or yawed out of the wind. During normal operation of the system, the wind direction should be perpendicular to the swept area of the rotor.

The yaw drive is controlled by a slow closed-loop control system. The yaw drive is operated by a wind vane, which is usually mounted on the top of the nacelle sensing the relative wind direction, and the wind turbine controller. In some designs, the nacelle is yawed to attain reduction in power during high winds.

In extremity, the turbine can be stopped with nacelle turned such that the rotor axis is at right angles to the wind direction. One of the more difficult parts of a wind turbine designs is the yaw system, though it is apparently simple. Especially in turbulent wind conditions, the prediction of yaw loads is uncertain.

(VI) CONTROL SYSTEMS:

A wind turbine power plant operates in a range of two characteristic wind speed values referred to as Cut in wind speed u_{in} and Cut out wind speed u_{out}. The turbine starts to produce power at Cut in wind speed usually between 4 and 5 m/s. Below this speed, the turbine does not generate power. The turbine is stopped at Cut out wind speed usually at 25 m/s to reduce load and prevent damage to blades. They are designed to yield maximum power at wind speeds that lies usually between 12 and 15 m/s. It would not be economical to design turbines at strong winds, as they are too rare. However, in case of stronger winds, it is necessary to waste part of the excess energy to avoid damage on the wind turbine. Thus, the wind turbine needs some sort of automatic control for the protection and operation of wind turbine. The functional capabilities of the control system are required for:

i Controlling the automatic startup

ii Altering the blade pitch mechanism

iii Shutting down when needed in the normal and abnormal condition

iv Obtaining information on the status of operation, wind speed, direction and power production for monitoring purpose

As can be seen in figure 1 (c), the nacelle consists of several components. They are the generator, yaw motor, gearbox, tower, yaw ring, main bearings, main shaft, hub, blade, clutch, brake, blade and spinner.

Other equipment that is not shown in the figure might include the anemometer, the controller inside the nacelle, the sensors and so on. The generator is responsible for the conversion of mechanical to electrical energy.

Yaw motor is used power the yaw drive to turn the nacelle to the direction of the wind. The gearbox is used to connect the low-speed shaft (main shaft in the figure) to the high-speed shaft which drives the generator rotor. The brake is used to stop the main shaft from over speeding.

The blades are used to extract the kinetic power from the wind to mechanical power i.e. lifting and rotating the blades. The tower is made from tubular steel or steel lattice and it is usually very high in order to expose the rotor blades to higher wind speed.

2. MODELING OF CASE STUDY

2.1 DFIG WIND TURBINE WITH ENERGY STORAGE

Fig.2.1 shows the basic configuration of a DFIG wind turbine equipped with a supercapacitor-based ESS. The low-speed wind turbine drives a high-speed DFIG through a gearbox. The DFIG is a wound-rotor induction machine. It is connected to the power grid at both stator and rotor terminals. The stator is directly connected to the grid, while the rotor is fed through a variable-frequency converter, which consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back to back through a dc link and usually has a rating of a fraction (25%–30%) of the DFIG nominal power. As a consequence, the WTG can operate with the rotational speed in a range of ±25%–30% around the synchronous speed, and its active and reactive powers can be controlled independently.

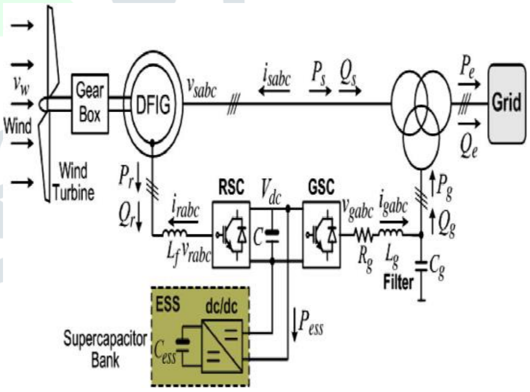


Fig. 2.1. Configuration of a DFIG wind turbine equipped with a super capacitor
ESS connected to a power grid.

In this project, an ESS consisting of a super capacitor bank and a two-quadrant dc/dc converter is connected to the dc link of the DFIG converters.

The ESS serves as either a source or a sink of active power and therefore contributes to control the generated active power of the WTG. The value of the capacitance of the super capacitor bank can be determined by

$$C_{\text{ess}} = \frac{2P_nT}{V_{SC}^2} \qquad (1)$$

Where *C*ess is in farads, *Pn* is the rated power of the DFIG in watts, *V*SC is the rated voltage of the supercapacitor bank in volts, and *T* is the desired time period in seconds that the ESS can supply/store energy at the rated power (*Pn*) of the DFIG.

The use of an ESS in each WTG rather than a large single central ESS for the entire wind farm is based on two reasons. First, this arrangement has a high reliability because the failure of a single ESS unit does not affect the ESS units in other WTGs. Second, the use of an ESS in each WTG can reinforce the dc bus of the DFIG converters during transients, thereby enhancing the low-voltage ride through capability of the WTG.

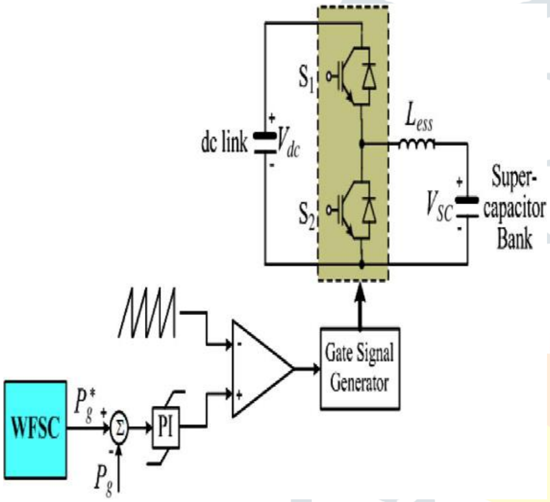


Fig. 2.3 Configuration and control of the ESS.

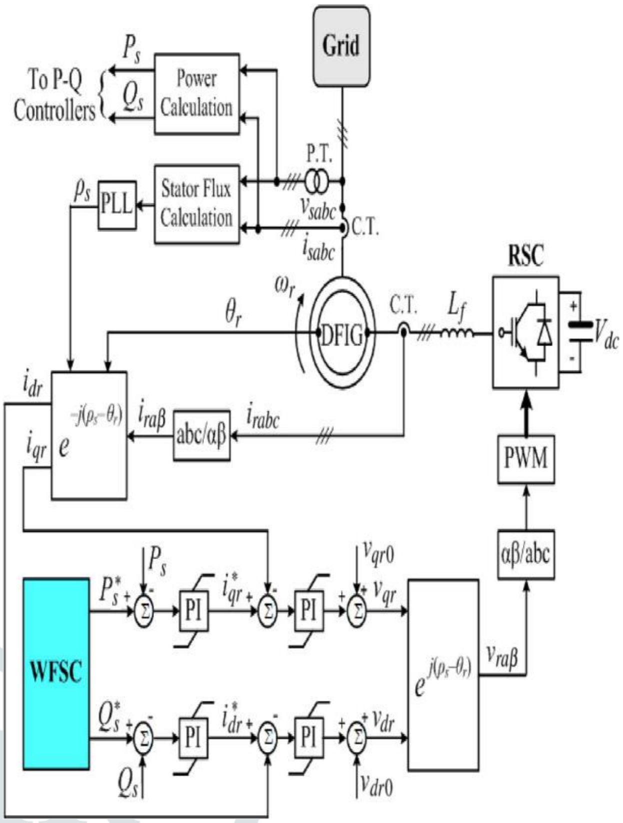


Fig. 2.2. Overall vector control scheme of the RSC.

2.2 CONTROL OF INDIVIDUAL DFIG WIND TURBINE

The control system of each individual DFIG wind turbine generally consists of two parts: 1) the electrical control of the DFIG and 2) the mechanical control of the wind turbine blade pitch angle and yaw system. Control of the DFIG is achieved by controlling the RSC, the GSC, and the ESS (see Fig. 2.1). The control objective of the RSC is to regulate the stator-side active power Ps and reactive power Qs independently. The control objective of the GSC is to maintain the dc-link voltage Vdc constant and to regulate the reactive power Qg that the GSC exchanges with the grid. The control objective of the ESS is to regulate the active power Pg that the GSC exchanges with the grid. In this paper, the mechanical control of the wind turbine blade pitch angle is similar.

2.2.1. Control of the RSC

Fig. 2.2 shows the overall vector control scheme of the RSC, in which the independent control of the stator active power Ps and reactive power Qs is achieved by means of rotor current regulation in a stator-flux oriented synchronously rotating reference frame. Therefore, the overall RSC control scheme consists of two cascaded control loops. The outer control loop regulates the stator active and reactive powers independently, which generates the reference signals i^*_{dr} and i^*_{qr} of the d- and q-axis current components, respectively, for the inner-loop current regulation. The outputs of the two current controllers are compensated by the corresponding cross-coupling terms v_{dr0} and v_{qr0}, respectively, to form the total voltage signals v_{dr} and v_{qr}. They are then used by the pulse width modulation (PWM) module to generate the gate control signals to drive the RSC. The reference signals of the outer-loop power controllers are generated by the high-layer WFSC.

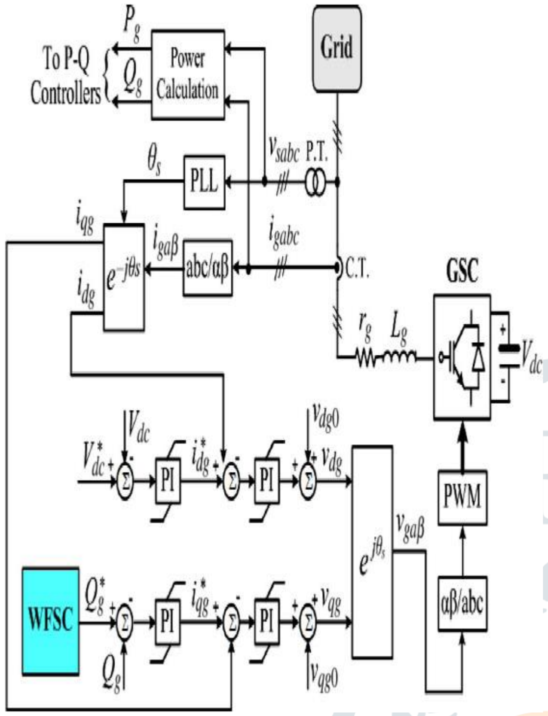


Fig. 2.4 Overall vector control scheme of the GSC.

2.2.2. Control of the GSC

Fig. 2.4 shows the overall vector control scheme of the GSC, in which the control of the dc-link voltage V_{dc} and the reactive power Q_g exchanged between the GSC and the grid is achieved by means of current regulation in a synchronously rotating reference frame. Again, the overall GSC control scheme consists of two cascaded control loops. The outer control loop regulates the dc-link voltage V_{dc} and the reactive power Q_g, respectively, which generates the reference signals i^*_{dg} and i^*_{qg} of the *d*- and *q*-axis current components, respectively, for the inner-loop current regulation. The outputs of the two current controllers are compensated by the corresponding cross coupling terms v_{dg0} and v_{qg0}, respectively, to form the total voltage signals v_{dg} and v_{qg}. They are then used by the PWM module to generate the gate control signals to drive the GSC. The reference signal of the outer-loop reactive power controller is generated by the high-layer WFSC.

2.2.3. Configuration and Control of the ESS

Fig. 2.3 shows the configuration and control of the ESS. The ESS consists of a supercapacitor bank and a two-quadrant dc/dc converter connected to the dc link of the DFIG. The dc/dc converter contains two insulated-gate bipolar transistor (IGBT) switches S1 and S2. Their duty ratios are controlled to regulate the active power *Pg* that the GSC exchanges with the grid. In this configuration, the dc/dc converter can operate in two different modes, i.e., buck or boost mode, depending on the status of the two IGBT switches. If S1 is open, the dc/dc converter operates in the boost mode; if S2 is open, the dc/dc converter operates in the buck mode.

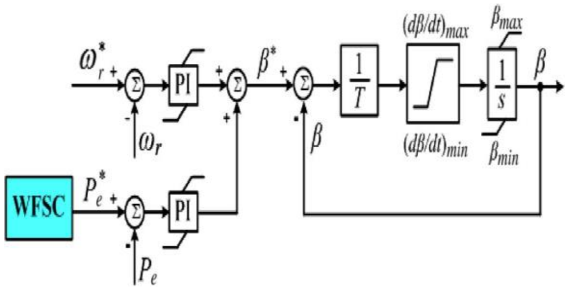


Fig. 2.5 Blade pitch control for the wind turbine.

The duty ratio D_1 of S1 in the buck mode can be approximately expressed as

$$D_1 = \frac{V_{SC}}{V_{dc}} \qquad (2)$$

and the duty ratio D_2 of S2 in the boost mode is $D_2 = 1 - D_1$. In this paper, the nominal dc voltage ratio $V_{SC,n}/V_{dc,n}$ is 0.5, where VSC,n and Vdc,n are the nominal voltages of the supercapacitor bank and the DFIG dc link, respectively. Therefore, the nominal duty ratio $D_{1,n}$ of S_1 is 0.5.

The operating modes and duty ratios D_1 and D_2 of the dc/dc converter are controlled depending on the relationship between the active powers P_r of the RSC and P_g of the GSC. If P_r is greater than P_g, the converter is in buck mode and D_1 is controlled, such that the supercapacitor bank serves as a sink to absorb active power, which results in the increase of its voltage *VSC*. On the contrary, if P_g is greater than *Pr*, the converter is in boost mode and D_2 is controlled, such that the supercapacitor bank serves as a source to supply active power, which results in the decrease of its voltage *VSC*. Therefore, by controlling the operating modes and duty ratios of the dc/dc converter, the ESS serves as either a source or a sink of active power to control the generated active power of the WTG. In Fig. 2.3, the reference signal P^*_g is generated by the high-layer WFSC.

2.2.4. Wind Turbine Blade Pitch Control

Fig. 2.5 shows the blade pitch control for the wind turbine, where ω_r and P_e (= $P_s + P_g$) are the rotating speed and output active power of the DFIG, respectively. When the wind speed is below the rated value and the WTG is required to generate the maximum power, ω_r and P_e are set at their reference values, and the blade pitch control is deactivated. When the wind speed is below the rated value, but the WTG is required to generate a constant power less than the maximum power, the active power controller may be activated, where the reference signal P^*_e is generated by the high-layer WFSC and P_e takes the actual measured value. The active power controller adjusts the blade pitch angle to reduce the mechanical power that the turbine extracts from wind.

3. SUPERVISORY CONTROL THEORY

3.1 DOUBLY-FED ELECTRIC MACHINE

Doubly-fed electric machines are electric motors or electric generators that have windings on both stationary and rotating parts, where both windings transfer significant power between shaft and electrical system. Doubly-fed machines are useful in applications that require varying speed of the machine's shaft for a fixed power system frequency.

The supervisory control theory, also known as the Ramadge-Wonham framework, is a method for automatically synthesizing supervisors that restrict the behavior of a plant such that as much as possible of the given specifications are fulfilled. The plant is assumed to spontaneously generate events. The events are in either one of the following two categories controllable or uncontrollable. The supervisor observes the string of events generated by the plant and might prevent the plant from generating a subset of the controllable events. However, the supervisor has no means of forcing the plant to generate an event.

In its original formulation the SCT considered the plant and the specification to be modeled by formal languages, not necessarily regular languages generated by finite automata as was done in most subsequent work.

3.2 CLASSIFICATION

Electric machines are either Singly-Fed with one winding set that actively participates in the energy conversion process or Doubly-Fed with two active winding sets. The wound-rotor induction machine and the field-excited synchronous machine are singly-fed machines because only one winding set actively participates in the energy conversion process.

Examples of doubly-fed electric machines are the wound-rotor doubly-fed electric machine, the brushless wound-rotor doubly-fed electric machine, and the brushless doubly-fed induction electric machines.

3.3. FEATURES OF DOUBLY FED MACHINES

The wound-rotor doubly-fed electric machine is the only electric machine that operates with rated torque to twice synchronous speed for a given frequency of excitation (i.e., 7200 rpm @ 60 Hz and one pole-pair versus 3600 rpm for singly-fed electric machines). Higher speed with a given frequency of excitation gives lower cost, higher efficiency, and higher power density. In concept, any electric machine can be converted to a wound-rotor doubly-fed electric motor or generator by changing the rotor assembly to a multiphase wound rotor assembly of equal stator winding set rating.

If the rotor winding set can transfer power to the electrical system, the conversion result is a wound-rotor doubly-fed electric motor or generator with twice the speed and power as the original singly-fed electric machine. The resulting dual-ported transformer circuit topology allows very high torque current without core saturation, all by electronically controlling half or less of the total motor power for full variable speed control.

In practice, the classical wound-rotor doubly-fed "induction" electric motor or generator system has known issues of instability, high maintenance and inefficiency of an integral multiphase slip-ring assembly, and discontinuity about synchronous speed where induction ceases to exist. A practical wound-rotor doubly-fed electric machine system that does not rely exclusively on asynchronous (i.e., induction) principles while symmetrically motoring or generating over its entire speed range has never materialized from the electric machine establishment, despite years of research to find an evolutionary brushless, synchronous, and stable control technology.

Consequently, the wound-rotor doubly-fed induction electric machine has been forced into antiquity, except in large installations where efficiency and cost are critical over a limited speed range, such as wind turbines. This may change with recent Brushless Wound-Rotor Doubly-Fed Electric Machine technology development.

As do all electromagnetic electric machines, doubly fed machines need torque current to produce the torque. Because there are no permanent magnets in the doubly fed machine, magnetizing current is also needed to produce magnetic flux.

Magnetizing current and torque current are orthogonal vectors and do not add directly. Since the magnetizing current is much smaller than the torque current, it is only significant in the efficiency of the machine at very low torque.

Like wound rotor synchronous machines, the magnetic flux can be produced by the stator current, rotor current or by the combination of the both. For example, if all magnetizing current is supplied by the rotor windings, the stator will only have torque current and so unity power factor. At synchronous speed the rotor current has to be DC, as in ordinary synchronous machines. If the shaft speed is above or below synchronous speed, the rotor current must be AC at the slip frequency. Reactive power is used in the rotor winding when it is used to magnetize the machine in non-synchronous operation. Rotor current is also needed to produce torque in addition to magnetization. Thus active power is present in the rotor in addition to reactive power.

The frequency and the magnitude of the rotor voltage is proportional to the difference between the speed of the machine and the synchronous speed (the slip). At standstill, the frequency will be the same as the frequency in the stator; the voltage is determined by the ratio of the stator and rotor winding turns.

Thus if the number of turns is equal, the rotor has the same voltage as the stator. The doubly-fed machine is a transformer at standstill. The transformer-like characteristics are also present when it is rotating, manifesting itself especially during transients in the grid. Due to the voltage and current behavior described above the rotor will either require, or generate, active power depending on the speed and torque. If the machine is producing torque and operating as a motor, the rotor will generate power if the speed is below synchronous speed (sub synchronous operation).

At standstill all power fed in the stator (excluding losses) is returned via the rotor. The magnitude of the active power depends on the torque of the motor.

Thus if the motor has rated torque, rated power is circulating through the stator and rotor. Like all electric machines, the efficiency of the machine is not very good at low speeds because current is required to produce torque but little or no mechanical power is produced.

If the machine is operating as a motor at speeds over the synchronous speed (super synchronous operation), the mechanical power is fed in both through the stator and rotor.

As a consequence the efficiency is now better than with singly fed motors. For example, at maximum speed the doubly-fed electric machine with equal stator and rotor turns produces same torque at double speed (and thus twice the power) as a singly-fed electric machine. The losses, being roughly proportional to the torque, are quite the same. Thus efficiency, which is the power taken divided by the produced power, is better than singly-fed electric machines. Naturally one has to take into account the loss of the power electronic control equipment.

However, the frequency converter of the doubly fed machine has to control only 50% or less of the power of the machine, and thus has about half of the loss of the singly-fed machines' frequency converter that has to pass through 100 % of the power. Since efficiency is the ratio between the output power (i.e., input power minus the loss) to the input power, the magnetic core efficiency of a wound rotor doubly fed machine, which has just two winding sets (i.e., dual armature winding sets) of loss but shows twice the power for a given frequency and voltage of operation, is comparable to the magnetic core efficiency of permanent magnet machines with just one winding set (i.e., single armature winding set) of loss but without magnetizing current.

Coupled with the low power electronic controller, the wound-rotor doubly-fed electric machine system would be more efficient than permanent magnet machine systems without magnetizing current. For operation as a generator a similar situation exists.

At sub synchronous speeds the stator is generating the power but part of it has to be fed back to rotor. At super synchronous speeds both the rotor and stator are producing power to the grid.

Thus the current rating of the rotor converter is defined by the maximum active current required by the torque production and the maximum reactive current required to magnetize the machine. Changing of the direction of the rotation requires the swap of two stator phases near zero speed if symmetrical speed range in both directions is required. Further note, it is common to dimension the doubly fed machine to operate only at a narrow speed range around synchronous speed and thus further decrease the power rating (and cost) of the frequency converter in the rotor circuit.

Typical applications of doubly fed machines have been high power pumps and fans, hydro and wind generators, shaft generators for ships etc. where operating speed range has been quite narrow, less than ± 30 % of the synchronous speed and only small power is required in the sub synchronous range.

Due to the high rotor to stator winding turn ratio and the high voltage thus induced in the rotor at standstill, the starting of this kind of restricted operating speed range motor drive is usually done with rotor resistors in induction motor mode. When speed is in the operating speed range, the resistors are disconnected and the frequency converter is connected to the rotor. It is also possible to short circuit the stator and use the frequency converter in the induction motor control mode to accelerate the motor to the operating speed range. Generators, naturally, don't usually need any additional starting means because wind or water is used to accelerate the machine to the operating speed range.

3.4 DOUBLE FED INDUCTION GENERATOR (DFIG)

DFIG is an abbreviation for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly (see brushless doubly-fed electric machines), but there are problems with efficiency, cost and size. A better alternative is a brushless wound-rotor doubly-fed electric machine.

3.5 PRINCIPLE OF A DOUBLE FED INDUCTION GENERATOR CONNECTED TO A WIND TURBINE

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30 % operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (low voltage ride through The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault.

A doubly fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications., LVRT).

Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions.

Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30 %, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason.

3.6 SYSTEM MODEL:

The electrical model for the system is developed using dynamic phasors or complex space vectors in the anachronously rotating – reference frame. An illustration of the axes conventions The default convention assumed here aligns the -axis with the positive real axis and the -axis with the negative imaginary axis, and the complex vector. In certain instances it is convenient to locate the real and imaginary axes aligned with a particular complex vector, for instance , in which case the axes are designated and respectively, and the real and (negative) imaginary components with respect to the reference are designated and , a respectively.

The following simplifying assumptions are made in the development of the model.

1) The iron losses, mechanical and power converter losses are negligible.

2) The magnetic circuit of the machine can be represented bya linear model.

3) The entire mechanical system can be modeled using a lumped inertia parameter referred to the electrical angle and speed of the induction generator.

4) The power converters can be modeled using state-space averaged representation to represent their low frequency dynamics.

5) The wind farm collection network to PCC is electrically stiff. The conventional DFIG T circuit is transformed into an equivalent circuit

The system equivalent circuit model under these assumptions The complete set of nonlinear state equations are

$$\frac{d\underline{\lambda}_s}{dt} = -\underline{\lambda}_s\left(\frac{R_s}{L_s}+j\omega_e\right)+\underline{i}_R R_s+\underline{v}_f+\underline{v}_i$$

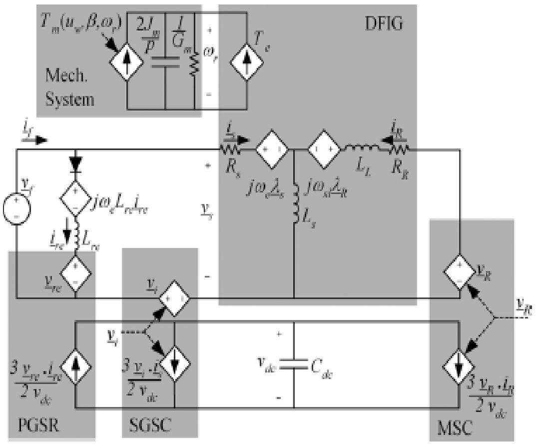
$$\frac{d\underline{i}_R}{dt} = \frac{1}{L_L}\Big[-\underline{i}_R\left(R_R+R_s+j\omega_{sl}L_L\right)\dots$$
$$+\underline{\lambda}_s\left(\frac{R_s}{L_s}+j\omega_r\right)+\underline{v}_R-\left(\underline{v}_f+\underline{v}_i\right)\Big]$$

$$\frac{d\underline{i}_{re}}{dt} = u(\underline{v}_f-\underline{v}_{re})\left(\frac{\underline{v}_{re}-\underline{v}_f}{L_{re}}-j\omega_e\underline{i}_{re}\right)$$

$$\frac{dv_{dc}}{dt} = \frac{-3}{2v_{dc}C_{dc}}\left[\underline{v}_i\cdot\left(\frac{\underline{\lambda}_s}{L_s}-\underline{i}_R\right)-\underline{v}_{re}\cdot\underline{i}_{re}+\underline{v}_R\cdot\underline{i}_R\right]$$

$$\frac{d\omega_r}{dt} = \frac{p}{2J_m}\left[\frac{3p\;\underline{\lambda}_s\times\underline{i}_R|}{4}+T_m-\frac{2\omega_r}{pG_m}\right]$$

where $u(\cdot)$ is the unit step function.



The complex vector dynamic state equations are used form the evaluation of steady state properties and the development of control laws. The dynamic states of the system include the stator flux, , rotor current , rectifier current , dc link voltage, , and rotor speed, . Controllable inputs to the system include the complex voltage vectors for the MSC and SGSC, and respectively.

Since the PGSR is a passive network, its conduction state is determined by the state of the diode which conducts when the voltage is greater than.

The mechanical power generated at the wind turbine shaft is proportional to the coefficient of performance and the cube of the wind speed. The mechanical torque production due to wind energy capture can be throttled via the blade pitch actuators.

3.7 DFIG CONTROL:

When the DFIG is connected to a network, connection must be done in three steps which are presented below the first step is the regulation of the statoric voltages with the network voltages as reference the second step is the stator connection to this network. As the voltages of the two devices are synchronized, this connection can be done without problem. Once this connection is achieved, the third step, which constitutes the topic of this paper, is the power regulation between the stator and the network.

3.8 BRUSHLESS DOUBLY-FED INDUCTION ELECTRIC GENERATOR:

Brushless doubly-fed induction electric generator (i.e., electric motors or electric generators) are constructed by adjacently placing two multiphase winding sets with unlike pole-pairs on the stator body. With unlike pole-pairs between the two winding sets, low frequency magnetic induction is assured over the speed range.

One of the stator winding sets (power winding) is connected to the grid and the other winding set (control winding) is supplied from a frequency converter. The shaft speed is adjusted by varying the frequency of the control winding. As a doubly-fed electric machine, the rating of the frequency converter need only be fraction of the machine rating.

The brushless doubly-fed induction generator does not utilize core real-estate efficiently and the dual winding set stator assembly is physically larger than other electric machines of comparable power rating. In addition, a specially designed rotor assembly tries to focus most of the mutual magnetic field to follow an indirect path across the air-gap and through the rotor assembly for inductive coupling (i.e., brushless) between the two adjacent winding sets. As a result, the adjacent winding sets are excited independently and actively participate in the electro-mechanical energy conversion process, which is a criterion of doubly-fed electric machines.

The type of rotor assembly determines if the machine is a reluctance or induction doubly-fed electric machine. The constant torque speed range is always less than 1800 rpm @ 60 Hz because the effective pole count is the average of the unlike pole-pairs of the two active winding sets. Brushless doubly-fed electric machines incorporate a poor electromagnetic design that compromises physical size, cost, and electrical efficiency, to chiefly avoid a multiphase slip ring assembly. Although brushless doubly-fed electric machines have not seen commercial success since their conception in the early 1970s, the promise of a low cost, highly efficient electronic controller keeps the concept under perpetual study, research, and development.

3.9 BRUSHLESS WOUND-ROTOR DOUBLY-FED ELECTRIC GENERATOR:

The brushless wound-rotor doubly-fed electric generator incorporates the electromagnetic structure of the wound-rotor doubly-fed electric machine, but replaces the traditional multiphase slip ring assembly with a brushless means to independently power the rotor winding set with multiphase AC power.

The torque of the wound-rotor doubly-fed electric machine is dependent on both slip and position, which is a classic condition for instability.

For stable operation, the frequency and phase of the multiphase AC power must be synchronized and fixed instantaneously to the speed and position of the shaft, which is not trivial at any speed and particularly difficult about synchronous speed where induction no longer exists. If these conditions are met, all the attractive attributes of the wound-rotor doubly-fed electric machine, such as high power density, low cost, ultra-high efficiency, and ultra-high torque potential, are realized without the traditional slip-ring assembly and instability problems. One company has patented and is selling a brushless, fully stable, synchronous wound-rotor doubly-fed electric machine with symmetric quality of motoring or generating. Another brushless wound-rotor construction invented by Lars Gertmar has been described in the patent application.

3.10 WOUND-ROTOR DOUBLY-FED ELECTRIC GENERATOR CONSTRUCTION

Two multiphase winding sets with similar pole-pairs are placed on the rotor and stator bodies, respectively. The wound-rotor doubly-fed electric machine is the only electric machine with two independent active winding sets, the rotor and stator winding sets, occupying the same core volume as other electric machines.

The doubly fed generator operation at unity stator power factor requires higher flux in the air-gap of the machine than when the machine is used as wound rotor induction machine. It is quite common that wound rotor machines not designed to doubly fed operation saturate heavily if doubly fed operation at rated stator voltage is attempted. Thus a special design for doubly fed operation is necessary.

A multiphase slip ring assembly (i.e., sliding electrical contacts) is traditionally used to transfer power to the rotating (moving) winding set and to allow independent control of the rotor winding set. The slip ring assembly requires maintenance and compromises system reliability, cost and efficiency.

3.11 ELECTRONIC CONTROL:

The electronic controller, a frequency converter, conditions bi-directional (i.e., four quadrant), speed synchronized, and multiphase electrical power to at least one of the winding sets (generally, the rotor winding set). Using four quadrant control, which must be continuously stable throughout the speed range, a wound-rotor doubly-fed electric machine with two poles (i.e., one pole-pair) has a constant torque speed range of 7200 rpm when operating at 60 Hz. However, in high power applications two or three pole-pair machines with respectively lower maximum speeds are common.

The electronic controller is smaller, less expensive, more efficient, and more compact than electronic controllers of singly-fed electric machine because in the simplest configuration, only the power of the rotating (or moving) active winding set is controlled, which is less than half the total power output of the electric machine. Due to the lack of damper windings used in synchronous machines, the doubly fed electric machines are susceptible to instability without stabilizing control. Like any synchronous machine, losing synchronism will result in alternating torque pulsation and other related consequences.

Doubly-fed electric machines require electronic control for practical operation and should be considered an electric machine system or more appropriately, an adjustable-speed drive.

3.12 EFFICIENCY:

Neglecting the slip ring assembly, the theoretical electrical loss of the wound-rotor doubly-fed machine in super synchronous operation is comparable to the most efficient electric machine systems available (i.e., the synchronous electric machine with permanent magnet assembly) with similar operating metrics because the total current is split between the rotor and stator winding sets while the electrical loss of the winding set is proportional to the square product of the current flowing through the winding set.

Further considering the electronic controller conditions less than 50% of the power of the machine, the wound-rotor doubly-fed electric motor or generator (without brushes and with stable control at any speed) theoretically shows nearly half the electrical loss (i.e., winding set loss) of other electric motor or generator systems of similar rating.

3.13 POWER DENSITY

Neglecting the slip ring assembly and considering similar air-gap flux density, the physical size of the magnetic core of the wound-rotor doubly-fed electric machine is smaller than other electric machines because the two active winding sets are individually placed on the rotor and stator bodies, respectively, with virtually no real-estate penalty. The constant-torque speed range is up to 7200 rpm @ 60 Hz with 2 poles compared to 3600 rpm @ 60 Hz with 2 poles for other electric machines. In theory, the core volume is nearly half the physical size (i.e., winding set loss) of other electric motor or generator systems of similar rating.

3.14 COST

Neglecting the slip ring assembly, the theoretical system cost is nearly 50% less than other machines of similar rating because the power rating of the electronic controller, which is the significant cost of any electric machine system, is 50% (or less) than other electric motor or generator systems of similar rating.

3.15 WIND FARM SUPERVISORY CONTROL

The objective of the WFSC is to generate the reference signals for the outer-loop power controllers of the RSC and GSC, the controller of the dc/dc converter, and the blade pitch controller of each WTG, according to the power demand from or the generation commitment to the grid operator.

The implementation of the WFSC is described by the flowchart in Fig5.1, where P_d is the active power demand from or the generation commitment to the grid operator; v_{wi} and V_{essi} are the wind speed in meters per second and the voltage of the supercapacitor bank measured from WTG i ($i = 1, \ldots, N$), respectively; and N is the number of WTGs in the wind farm. Based on v_{wi}, the optimal rotational speed ω_{ti}, opt in radians per second of the wind turbine can be determined, which is proportional to the wind speed v_{wi} at a certain pitch angle β_i

$$\omega_{ti,\mathrm{opt}} = k(\beta_i)v_{wi} \qquad (3)$$

where k is a constant at a certain value of β_i. Then, the maximum mechanical power $P_{mi,\max}$ that the wind turbine extracts from the wind can be calculated by the well-known wind turbine aerodynamic characteristics

$$P_{mi,\max} = \frac{1}{2}\rho_i A_r v_{wi}^3 C_{Pi}(\lambda_{i,\mathrm{opt}}, \beta_i) \qquad (4)$$

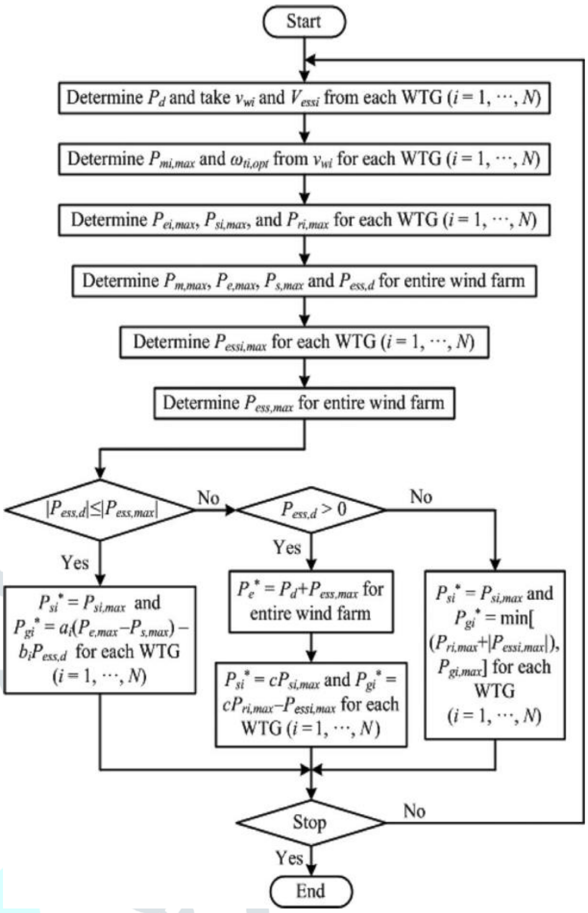
where ρ_i is the air density in kilograms per cubic meter; $A_r = \pi R^2$ is the area in square meters swept by the rotor blades, with R being the blade length in meters; and C_{Pi} is the power coefficient, which is a function of both tip-speed ratio λ_i and the blade pitch angle β_i, where λ_i is defined by

$$\lambda_i = \frac{\omega_{ti} R}{v_{wi}}. \qquad (5)$$

In (4), $\lambda_{i,\mathrm{opt}}$ is the optimal tip-speed ratio when the wind turbine rotates with the optimal speed $\omega_{ti,\mathrm{opt}}$ at the wind speed v_{wi}.

$$P_{ei,\max} = P_{mi,\max} - P_{Li} = P_{si,\max} + P_{ri,\max} \qquad (6)$$

Given $P_{mi,\max}$, the maximum active power $P_{ei,\max}$ generated by the WTG can be estimated by taking into account the power losses of the WTG



where P_{Li} is the total power losses of WTG i, which can be estimated by the method in; $P_{si,\max}$ and $P_{ri,\max}$ are the maximum DFIG stator and rotor active powers of WTG i, respectively. In terms of the instantaneous variables in Fig. 3.1,

The stator active power P_s can be written in a synchronously rotating dq reference frame as follows:

$$\begin{aligned} P_s &= \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \\ &\approx \frac{3}{2}\left[\omega_s L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) + r_s\left(i_{ds}^2 + i_{qs}^2\right)\right] \qquad (7) \end{aligned}$$

where vds and vqs are the d- and q-axis voltage components of the stator windings, respectively; ids and iqs are the stator d- and q-axis current components, respectively; idr and iqr are the rotor d- and q-axis current components, respectively; ωs is the rotational speed of the synchronous reference frame; and rs and Lm are the stator resistance and mutual inductance, respectively. Similarly, the rotor active power is calculated by

$$\begin{aligned} P_r &= \frac{3}{2}(v_{dr}i_{dr} + v_{qr}i_{qr}) \\ &\approx \frac{3}{2}\left[-s\omega_s L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) + r_r\left(i_{dr}^2 + i_{qr}^2\right)\right] \qquad (8) \end{aligned}$$

where *vdr* and *vqr* are the *d*- and *q*-axis voltage components of the rotor windings, respectively; *s* is the slip of the DFIG defined by

$$s = (\omega_s - \omega_r)/\omega_s \tag{9}$$

where ωr is the DFIG rotor speed. (7) and (8) yield

$$s = -\frac{P_r - 3i_r^2 r_r}{P_s - 3i_s^2 r_s} \tag{10}$$

Where $i_s = \sqrt{i_{ds}^2 + i_{qs}^2}/2$

and

$$i_r = \sqrt{i_{dr}^2 + i_{qr}^2}/2.$$

If neglecting the stator copper loss $3i^2_s r_s$ and rotor copper loss $3i^2_r\ r_r$ of the DFIG, the relationship between the stator and rotor active powers can be approximated by

$$P_r = -sP_s. \tag{11}$$

According to (6) and (10) [or (11)], $P_{si,\max}$ and $P_{ri,\max}$ of each WTG can be determined. Then, the total maximum mechanical power $P_{m,\max}$, DFIG output active power $P_{e,\max}$, and stator

According to (6) and (10) [or (11)], $P_{si,\max}$ and $P_{ri,\max}$ of each WTG can be determined. Then, the total maximum mechanical power $P_{m,\max}$, DFIG output active power $P_{e,\max}$, and stator

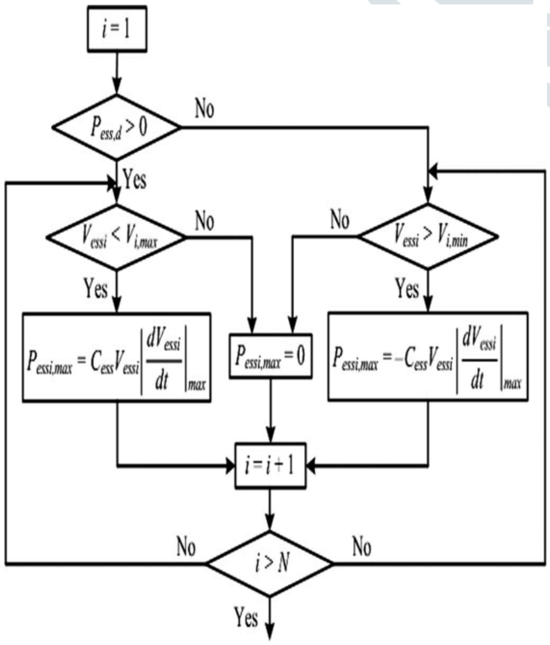


Fig.3.2 Flowchart of determination of $P_{essi,\max}$ for each WTG. active power $P_{s,\max}$ of all WTGs in the wind farm can be calculated as

$$P_{m,\max} = \sum_{i=1}^{N} P_{mi,\max} \tag{12}$$

$$P_{e,\max} = \sum_{i=1}^{N} P_{ei,\max} \tag{13}$$

$$P_{s,\max} = \sum_{i=1}^{N} P_{si,\max}. \tag{14}$$

In order to supply constant power P_d to the grid, the deviation $P_{\text{ess},d}$ between the demand/commitment P_d and the maximum generation $P_{e,\max}$ is the power that should be stored in or supplied from the ESSs of the WTGs

$$P_{\text{ess},d} = P_{e,\max} - P_d. \tag{15}$$

On the other hand, the capability of each ESS to store or supply power depends on the capacitance C_{ess} and the voltage $V_{\text{ess}i}$ of the supercapacitor bank. During normal operation, $V_{\text{ess}i}$ must be maintained within the following range:

$$V_{i,\min} < V_{\text{ess}i} < V_{i,\max} \tag{16}$$

where *Vi*,max and *Vi*,min are the maximum and minimum operating voltages of the supercapacitor bank, respectively. The maximum power $P_{\text{ess}i,\max}$ that can be exchanged between the supercapacitor bank and the DFIG dc link of WTG *i* can be determined by

$$P_{\text{ess}i,\max} = \pm C_{\text{ess}} V_{\text{ess}i} \left| \frac{dV_{\text{ess}i}}{dt} \right|_{\max} \tag{17}$$

where $|dV_{\text{ess}i}/dt|_{\max}$ is the maximum rate of voltage variations of the supercapacitor bank, which is related to the current limits of the supercapacitor bank. In (17), the positive sign indicates storing energy, while the negative sign indicates supplying energy by the ESS. The calculation of $P_{\text{ess}i,\ \max}$ for each WTG is subjected to (16).

Fig.3.2 shows how to determine $P_{\text{ess}i,\max}$ for each WTG. If $P_{\text{ess},d} > 0$, extra power needs to be stored in the ESSs. In this case, if $V_{\text{ess}i} < V_{i,\max}$, $P_{\text{ess}i,\max}$ is calculated by (17) and takes the positive sign; otherwise, the ESS cannot store any power and *Pessi*,max = 0. On the contrary, if $P_{\text{ess},\ d} < 0$, active power needs to be supplied from the ESSs. In this case,

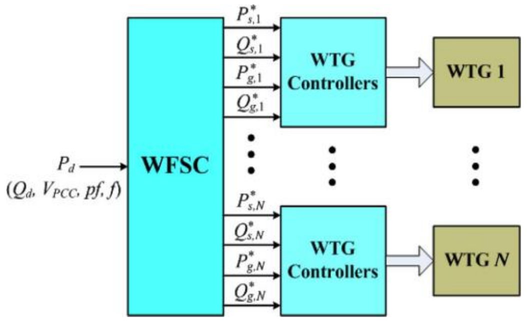


Fig.3.3 Proposed two-layer CPC scheme for the wind farm.

If $V_{essi} > V_{i,\min}$, *P*essi,max is calculated by (17) and takes the negative sign; otherwise, the ESS cannot supply any power and $P_{essi,\max} = 0$. As shown in Fig.5.1, once $P_{essi,\max}$ of each WTG is determined, the total maximum power $P_{ess,\max}$ that can be exchanged between the supercapacitor bank and the DFIG dc link of all WTGs can be determined by

$$P_{\mathrm{ess,max}} = \sum_{i=1}^{N} P_{\mathrm{ess}i,\mathrm{max}}. \qquad (18)$$

Finally,depending on the relationship of $P_{ess,d}$ and $P_{ess,\max}$,the reference signals P^*_{si} (see Fig. 2.2)and P^*_{gi} (see Fig. 2.3) of each WTG can be determined. Specifically, if $|P_{ess,d}| \le |P_{ess,\max}|$, P^*_{si} and P^*_{gi} can be determined directly, as shown in Fig.5.1, where the partition coefficients *ai*'s are calculated by

$$a_i = \frac{P_{ri,\mathrm{max}}}{P_{e,\mathrm{max}} - P_{s,\mathrm{max}}} \qquad (19)$$

and the partition coefficients *bi*'s are calculated by

$$b_i = \frac{P_{\mathrm{ess}i,\mathrm{max}}}{P_{\mathrm{ess,max}}}. \qquad (20)$$

The coefficients *ai* and *bi* have the following feature:

$$\sum_{i=1}^{N} a_i = 1 \qquad \sum_{i=1}^{N} b_i = 1. \qquad (21)$$

If $|P_{ess,d}| > |P_{ess,\max}|$, depending on the sign of $P_{ess,d}$, P^*_{si} and P^*_{gi} can be determined, as shown in Fig 5.1. If *P*ess,*d* is positive, the ESSs of the WTGs store active power, and the total active power generated by all DFIGs is P^*_e , which is less than $P_{e,\max}$. Therefore, a scaling factor *c* is defined as follows:

$$c = \frac{P_e^*}{P_{e,\mathrm{max}}} \qquad (22)$$

and P^*_{si} and P^*_{gi} can be determined by using the scaling factor.

If $P_{ess,d}$ is negative, the ESSs of the WTGs supply active power, the RSC of each WTG is controlled to generate the maximum stator active power $P_{si,\max}$, and the ESS of each WTG is controlled to generate active power of P^*_{gi}, where *Pgi*,max is the maximum value of P_{gi} depending on the maximum power capacity of the GSC.

Fig. 4.3 shows the block diagram of the proposed two-layer CPC scheme for the wind farm, where *Pd* is the active power demand from or commitment to the grid operator. In practice, the value of *Pd* should take into account the generation capability of the wind farm and should be subjected to the following limit:

$$P_d \le \overline{P}_{e,\mathrm{max}} \qquad (23)$$

where *Pe*,max is the average value of *Pe*,max over the period that *Pd* will be constant and the value of *Pe*,max during the period can be obtained from short-term wind power prediction. This function allows the wind farm to be able to actively participate in automatic generation control, unit commitment, or frequency regulation of the grid, where the deviations between the available wind energy input and desired active power output are compensated by the ESSs. Under the condition of (23) and the ESS of a WTG has been fully filled up, then the power reference of the blade pitch controller in Fig. 2.4 is set at *Pd* by the WFSC to adjust the pitch angle to reduce the WTG output active power to *Pd*. Moreover, the implementation of the WFSC (Fig. 4.1) subject to (23) ensures that the use of the ESS does not need to increase the rating of the RSC or the GSC.

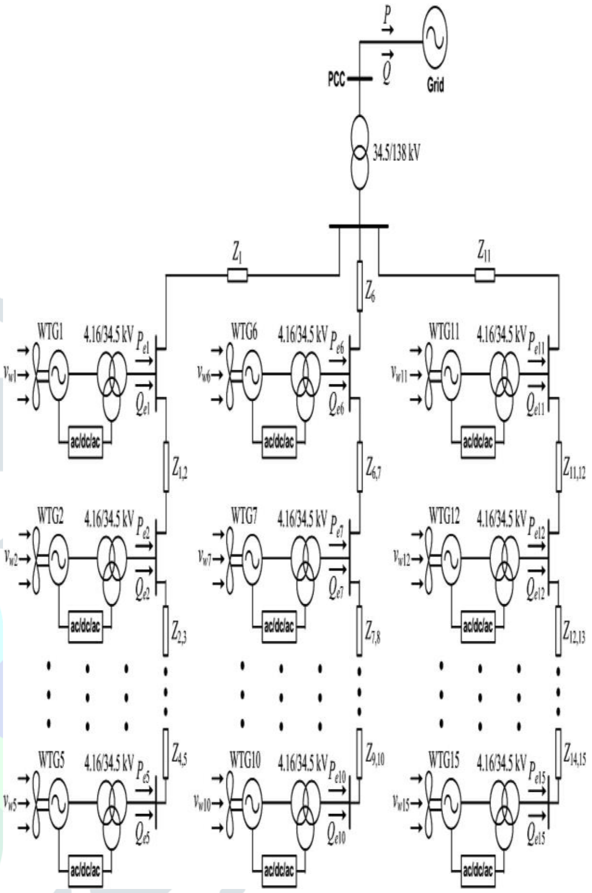


Fig.3.5 Configuration of a wind farm equipped with 15 DFIG wind turbines connected to a power grid.

The reactive power references of the RSC (Fig.2.3) and GSC (Fig.2.4) controllers can be determined by controlling the power factor (*pf*) or the voltage (*V*PCC) at the point of common coupling (PCC) of the wind farm at the desired value or to supply a desired amount of reactive power as required by the grid operator. However, these issues are not in the scope of this paper. In this paper, the reactive power references of all RSC and GSC controllers are simply set as zero.

4. SIMULATION RESULTS

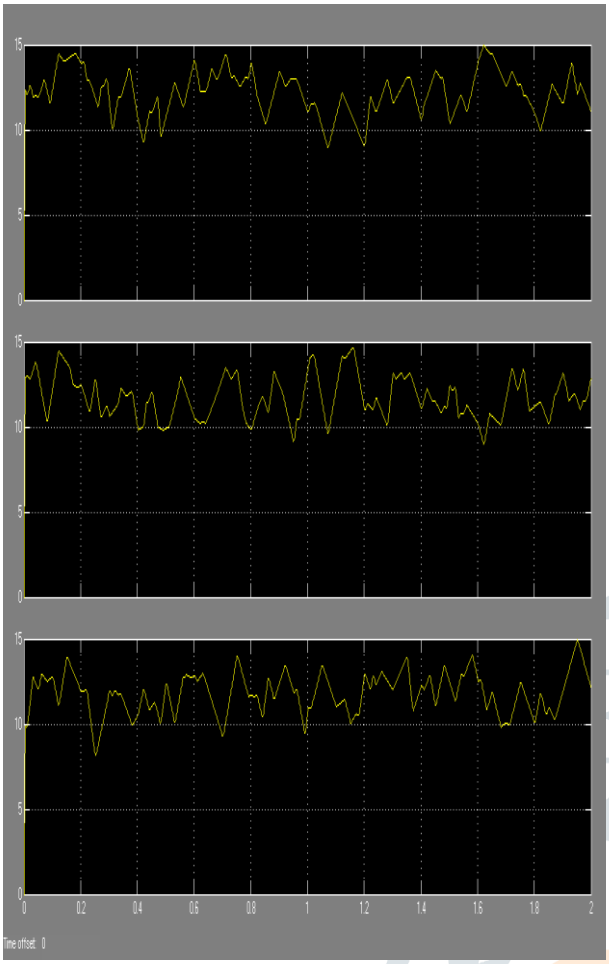


Fig 4.1 **Wind speed profiles of WTG1, WTG6, and WTG11**

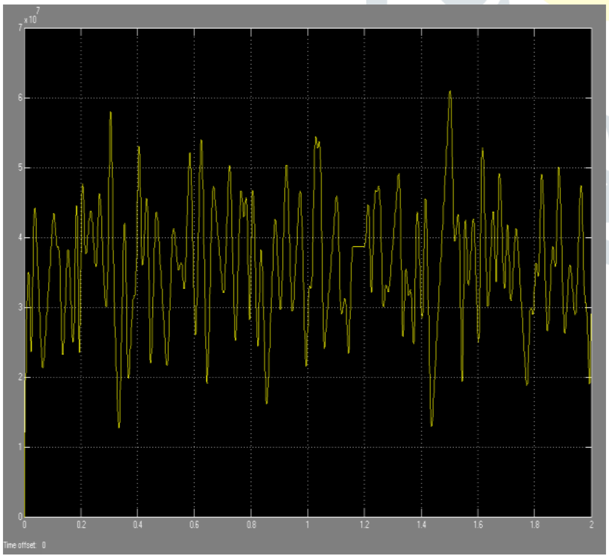


Fig4.2 **Without** ESS **and prosposed cpc scheme**

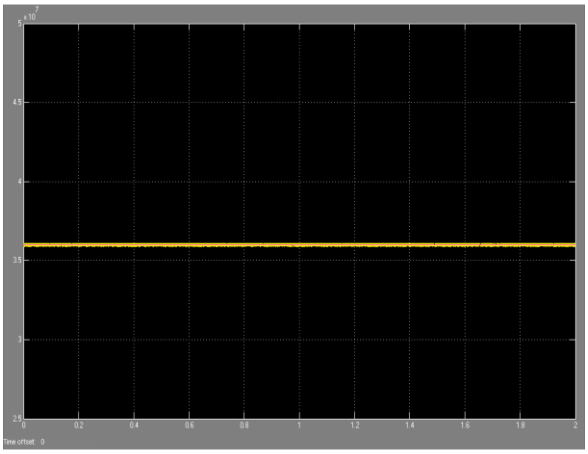


Fig4.3 with ESS and **Proposed CPC method**

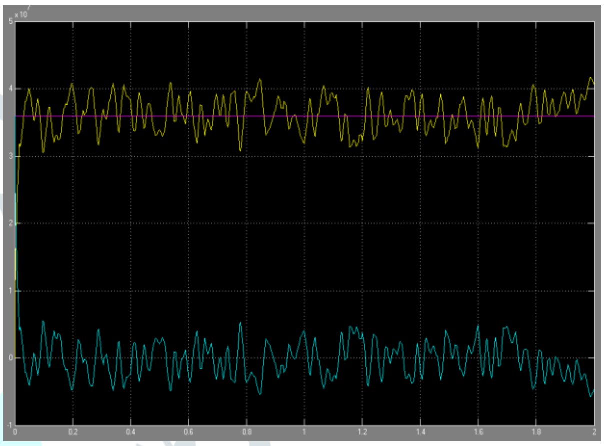


Fig 4.4 Active powers of individual WTGs.

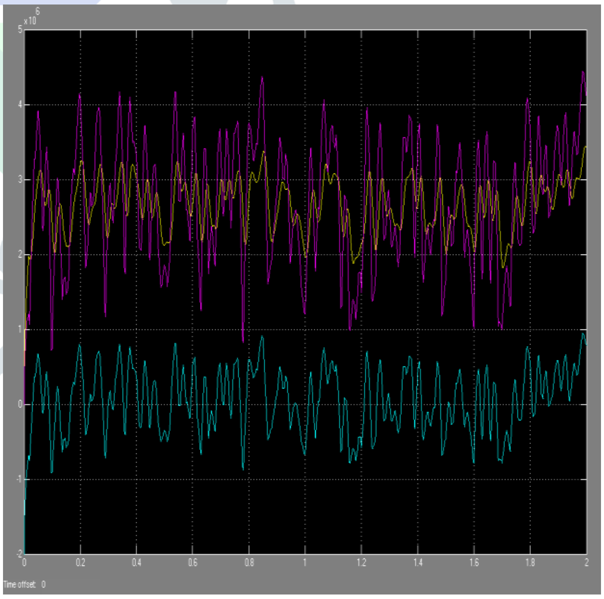


Fig 4.5 stator active power, GSC active power and total active power of WTG1

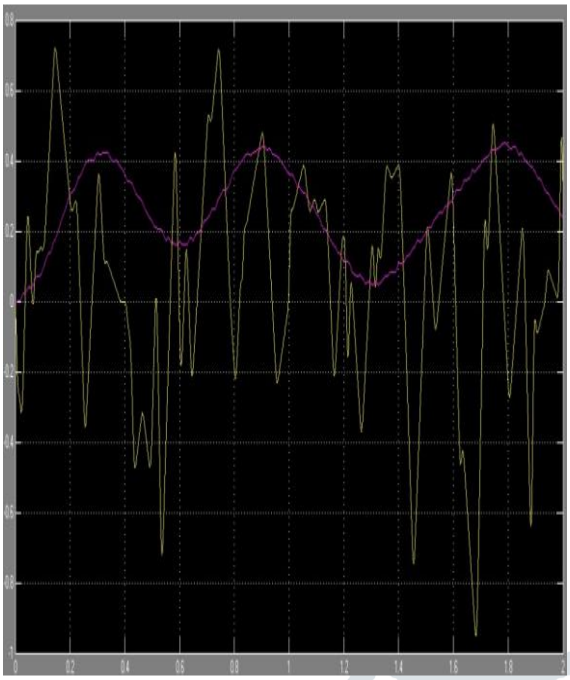


Fig 4.6 Rotor active power and supply by the ESS of WTG1

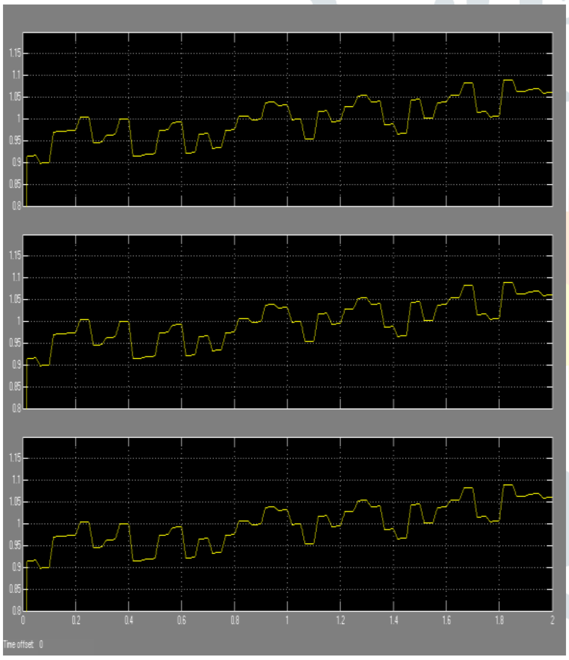


Fig 4.7 Voltages of the super capacitor banks of WTG1, WTG6, and WTG11

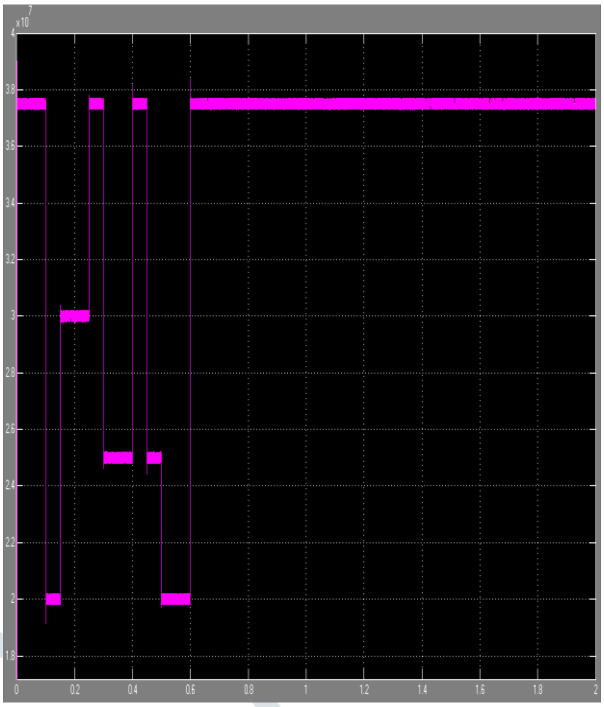


Fig 4.8 Power tracking performance of the wind farm during step changes in demand from the grid operator

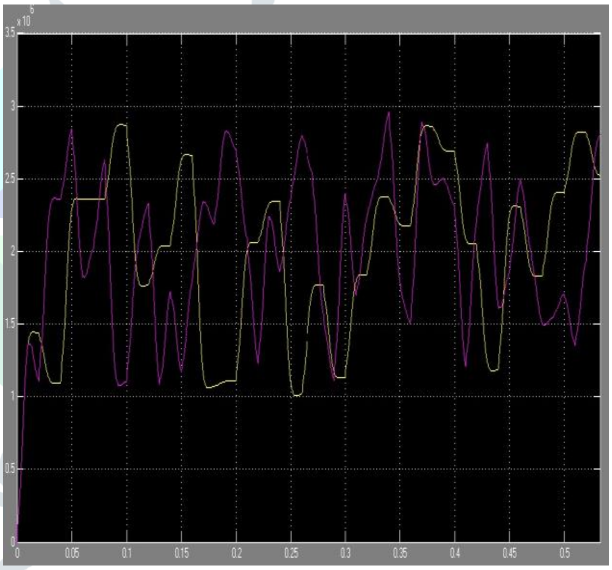


Fig 4.9 Total active power output of WTG1 and WTG5 during step changes in demand from the grid opertor

5. CONCLUSION

This project has proposed a novel two-layer CPC scheme for a wind farm equipped with DFIG wind turbines. Each wind turbine is equipped with a supercapacitor-based ESS, which is connected to the dc link of the DFIG through a two-quadrant dc/dc converter. The ESS serves as either a source or a sink of active power to control the generated active power of the DFIG wind turbine. Each individual DFIG wind turbine and its ESS are controlled by low-layer WTG controllers, which are coordinated by a high-layer WFSC to generate constant active power as required by or committed to the grid operator. Simulation studies have been carried out for a wind farm equipped with 15 DFIG wind turbines to verify the effectiveness of the proposed CPC scheme. Results have shown that the proposed CPC scheme enabled the wind farm to effectively participate in unit commitment and active power and frequency regulations of the grid. The proposed system and control scheme provides a solution to help achieve high levels of penetration of wind power into electric power grids.

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