

DOUBLY FED INDUCTION GENERATOR FOR CONSTANT POWER CONTROL AND FAULTS

Syed Abdur Rauf Magrabi¹, Shiv Shanker Kumar²

^{1,2} Department of Electrical & Electronics Engineering,

Sphoorthy Engineering College, Nadargul (V), R.R. District Hyderabad. 501510

ABSTRACT

This paper proposes a two-layer constant-power control (CPC) scheme for a wind farm equipped with doubly fed induction generator (DFIG) wind turbines, where each WTG is equipped with a super capacitor energy storage system (ESS). The CPC consists of a high-layer wind-farm supervisory controller (WFSC) and multiple low-layer WTG controllers. The high-layer WFSC generates the active-power references for the low-layer WTG controllers of each individual DFIG wind turbine according to the active-power demand from 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. An ESS consisting of SMES systems basically consist of a large coil, AC/DC converters and cooling units. The conductors used in the coil are superconductors, and therefore powerful cooling units need to be employed to maintain the superconductivity feature of the conductors. AC/DC converters convert the available AC voltage into DC form which is required for energy storage. By proper control, the AC/DC converters invert the stored DC energy into AC form so that it can be utilized. 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. Simulation studies are carried out in PSCAD/EMTDC on a wind farm equipped with 15 DFIG wind turbines to verify the effectiveness of the proposed control scheme.

Keywords: CPC, WTG, ESS, DFIG, AC/DC converter and MATLAB

I INTRODUCTION

Wind turbine generators (WTGs) are usually controlled to generate maximum electrical power from wind under normal wind conditions. However, because of the variations of 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 grid frequency regulation, unit commitment, or to supply a constant amount of active power as required by the grid operator. 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 (EWEA) 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 participate in grid frequency regulation as well as to supply the desired amount of active power for power flow control. To meet the requirements of frequency and active power regulation, energy storage devices will be required to dynamically match the intermittency of wind energy. In , the authors investigated and compared different feasible electrical energy storage technologies for intermittent renewable energy generation, such as wind power. The use of super capacitors or batteries as energy storage devices for WTGs has been studied by some researchers. However, these studies only focused on control and operation of individual WTGs and did not investigate the issues of WTGs to participate in grid regulation.

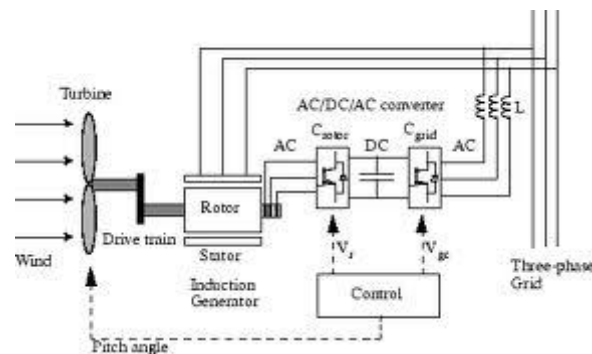


Figure 1: shows the basic configuration of a DFIG wind turbine equipped with a superconducting magnetic ESS.

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 $\pm 25\%$ –30% around the synchronous speed, and its active and reactive powers can be controlled independently. 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. 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. Usually the stator winding is directly connected to the three-phase grid and the three-phase rotor winding is fed from the grid through a rotating or static frequency converter. Doubly fed machines are typically used in applications that require varying speed of the machine's shaft in a limited range around the synchronous speed, for example $\pm 30\%$, because the power rating of the

frequency converter is reduced similarly. Today doubly fed drives are the most common variable speed wind turbine concept.

II FEATURES OF DOUBLY FED MACHINES

The wound rotor doubly fed machine is the only electric machine that can be operated with rated torque to twice synchronous speed for a given frequency of excitation (i.e., 7,200 rpm with one pole-pair doubly fed machine when both stator and rotor are fed with 60 Hz versus 3,600 rpm for otherwise similar singly fed electric machine). In high power applications two or three pole-pair machines are common. Higher speed with rated torque means that doubly fed machines have lower cost per kW, higher efficiency, and higher power density. In concept, any multiphase 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 winding set. If the rotor winding set can transfer active or working power to the electrical system, the conversion result is a wound-rotor doubly fed electric motor or generator with higher speed and power rating than the original singly fed electric machine. These advantages can be achieved without core saturation, all by electronically controlling half or less of the total motor power for full variable speed control. As do all electromagnetic electric machines, doubly fed machines need torque current and magnetic flux to produce torque. Because there are no permanent magnets in the doubly fed machine, magnetizing current is 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. Furthermore, magnetizing current of the wound rotor doubly fed electric machine can be shared between the stator and rotor windings. If all magnetizing current is supplied by the rotor windings, the stator will only have torque current and so unity power factor. However, by optimal current sharing the total I^2R loss can be minimized. 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. Thus the rotor winding requires reactive power when it is used to magnetize the machine in non-synchronous operation. Torque production requires that rotor current also has a torque producing component 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 magnitude 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 active power fed in the stator (excluding losses) is

returned via the rotor. If the motor has rated torque, rated active power is circulating through the stator, rotor and frequency converter and only losses are taken from the grid. The mechanical power being the angular speed multiplied by the torque of the motor is zero at standstill. Thus like all electric machines, the efficiency of the machine is not very good at low speeds because losses depend on the current that 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, 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 total power produced, 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 to the input power, the magnetic core efficiency of a wound rotor doubly fed machine, which has just two 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 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 subsynchronous 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. Doubly fed electric machines outperform the others in supersynchronous speeds. They can operate at constant torque to twice synchronous speed if each active winding is rated at half the total power of the machine and can provide continuous operation between subsynchronous through supersynchronous speed range. Doubly fed machines do not produce more continuous rated torque per volume than singly fed machines. The bigger power rating is due to the higher speed attainable without weakening the magnetic flux. The short time maximum torque of a wound rotor doubly fed electric machine is, however, much higher than all other electric machines, including induction or permanent magnet machines, because increasing torque current does not directly increase air-gap flux, which leads to core saturation. In practice, torque current increase is only limited by the temperature of the windings and the maximum current capability of the rotor frequency converter. With one of the two armature winding sets residing on the rotor and stator body, respectively, the rotor real estate of the wound-rotor doubly fed machine actively participates in the energy conversion process, which is different from all other electric machines, including permanent magnet synchronous machines. As a result, the magnetic core of the wound-rotor doubly fed electric machine shows highest power density. 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. 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 $\pm 30\%$ of the synchronous speed and only small power is required in the subsynchronous range. Due to the high rotor to stator winding turns ratio that is typical in these applications 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. If the starting torque is low enough 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.

III. PRINCIPLE OF DOUBLY FED MACHINES

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 $\pm 30\%$ 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. 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 when the remaining voltage stays above 15% of the nominal voltage. 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. For zero voltage ride through it is common to wait until the dip ends because with zero voltage it is not possible to know the phase angle where the

reactive current should be injected. As a summary, 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. 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, 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.

IV DESIGN OF DOUBLY FED MACHINES

The converter C_{grid} is used to regulate the voltage of the DC bus capacitor. In addition, this model allows using C_{grid} converter to generate or absorb reactive power.

The control system, illustrated in the figure called Grid-Side Converter Control System, consists of:

- Measurement systems measuring the d and q components of AC positive-sequence currents to be controlled as well as the DC voltage V_{dc} .
- An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current I_{dgc_ref} for the current regulator (I_{dgc} = current in phase with grid voltage which controls active power flow).
- An inner current regulation loop consisting of a current regulator. The current regulator controls the magnitude and phase of the voltage generated by converter C_{grid} (V_{gc}) from the I_{dgc_ref} produced by the DC voltage regulator and specified I_{qr_ref} reference. The current regulator is assisted by feed forward terms which predict the C_{grid} output voltage.

The magnitude of the reference grid converter current I_{gc_ref} is equal to

$$\sqrt{I_{dgc_ref}^2 + I_{qr_ref}^2}$$

The maximum value of this current is limited to a value defined by the converter maximum power at nominal voltage. When I_{dgc_ref} and I_{qr_ref} are such that the magnitude is higher than this maximum value the I_{qr_ref} component is reduced in order to bring back the magnitude to its maximum value.

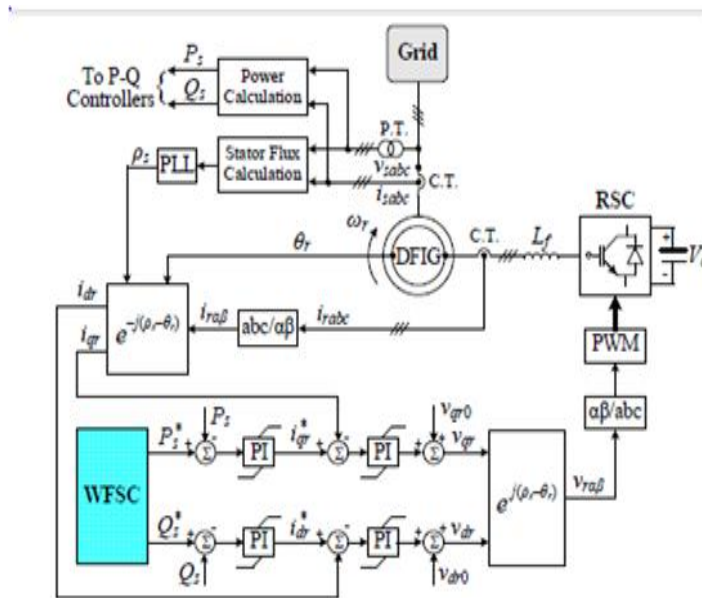


Figure 2: shows the design of DFIG using MATLAB.

The power loss as a function of transmitted power (or wind speed) was determined. However, for the wind-turbine application, the most important quantity is the energy delivered to the grid (electric energy capture). Accordingly, in this section the results in the previous section have been used to determine the energy capture (or energy efficiency) of the various systems. The distribution of wind speeds must be known. As mentioned earlier one commonly used probability density functions to describe the wind speed is the Rayleigh function. Given a probability density functions, $f(w)$, the average (or expected) value of the power, $P(w)$, can be found as

$$P_{avg} = \int_0^{\infty} P(w)f(w)dw$$

Where w is the wind speed.

It is not possible to obtain a full speed range with the DFIG system if the converter is smaller than the rated power of the turbine. The smaller the converter is, the more the WT will operate at a non-ideal tip-speed ratio, λ , for low wind speeds. The impact of having a smaller converter and thus a smaller rotor-speed range, i.e., the aerodynamic losses become higher. The converter losses are presented for different designs of the rotor-speed range, i.e., a smaller rotor-speed range implies smaller ratings of the converter. It can be seen in the figure that the converter losses are lower for smaller rotor-speed ranges (or smaller converter ratings). Note, as mentioned earlier, that the stator-to-rotor turns ratio has to be designed according to desired variable-speed range in order to minimize the converter losses.

V COMPARISON OF DOUBLY FED MACHINES WITH BRUSHLESS DOUBLY FED INDUCTION ELECTRIC MACHINE

Brushless doubly fed induction electric machine is 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.

VI SIMULATION RESULTS

The wind speed profiles applied to WTG1 (vw1), WTG6 (vw6), and WTG11 (vw11). The wind speeds across the three WTGs vary in a range of ± 3 m/s around their mean value of 12 m/s. The variations of wind speed cause fluctuations of the electrical quantities of the WTGs. If the wind farm is not equipped with any energy storage devices or the proposed CPC scheme, the wind-speed variations in the wind farm result in the significant fluctuations of the total output active power at the PCC. The wind-farm power output deviates significantly from the active-power demand of the grid operator. In future electric power grids where the penetration of wind power is high (e.g., 20%), such active power fluctuations can bring severe problems to grid operation. Total output active power of the wind farm with the power demand from the grid operator, where each WTG is equipped with an ESS as shown below figures

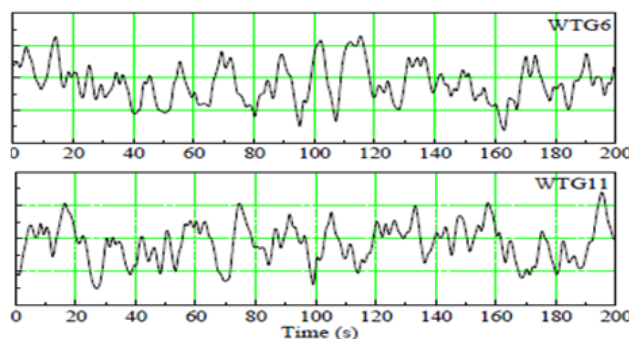


Figure 3: Shows the simulation results of different WTG.

The ESS stores energy when the WTG generates more active power than the demand and supplies energy when the WTG generates less active power than the demand. The resulting output power of the wind farm is therefore controlled at a constant value as required by the grid operator. The total stator active power P_s and the total GSC active power P_g of all WTGs, as well as the total output active power P (measured at PCC) of the wind farm.

Through the control of the proposed CPC scheme, the variations of the stator active power are exactly compensated by the variations of the GSC active power.

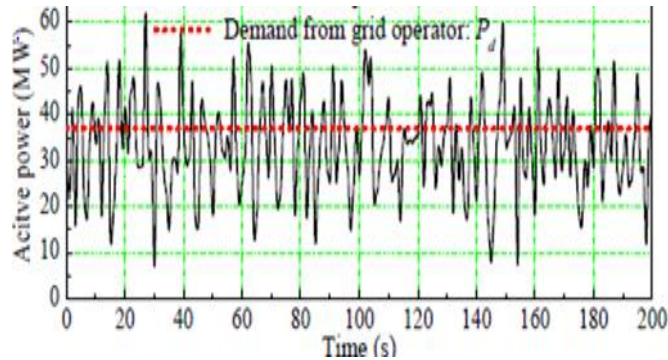


Figure 4 Shows the the active power demand w.r.t time.

Consequently, the total output active power of the wind farm is constant. However, the total output active power P_{ei} of each individual WTG, which is the sum of the stator active power P_{si} and the GSC active power P_{gi} , is usually not constant, as shown in below figure. The deviations between the RSC active power and the GSC active power of each WTG are stored in or supplied by the ESS. Figure 5: shows the wind farm output and demand from grid operator w.r.t time.

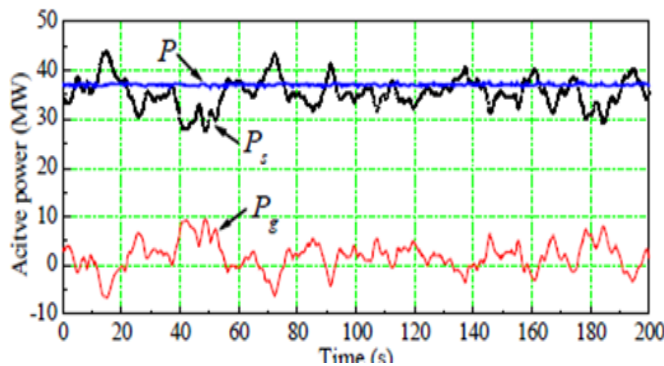
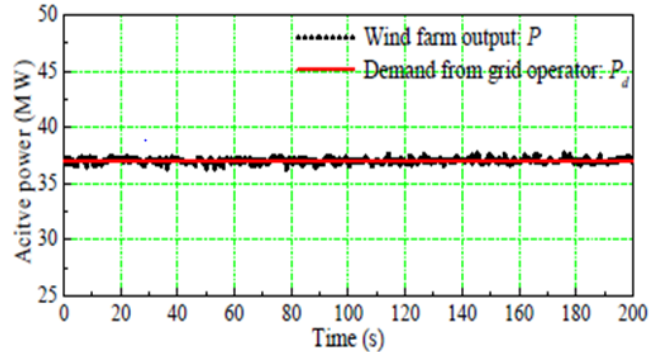


Figure 6: Shows the comparions input power and harmonics.

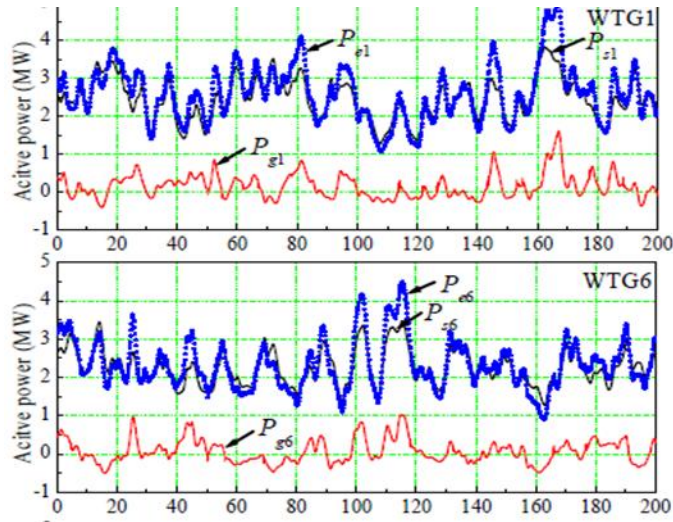


Figure 7 and 8: Shows the voltages of the supercapacitor banks of WTG1, WTG6, and WTG11.

These voltages are always maintained within the operating limits of [0.7, 1.1] p.u.

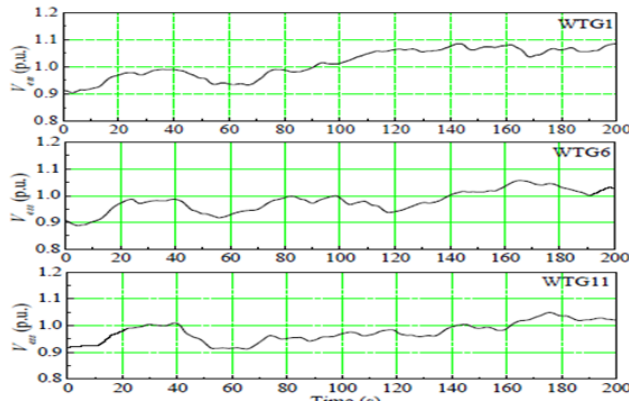


Figure 9: Shows the output of WTG1, WTG6 and WTG11.

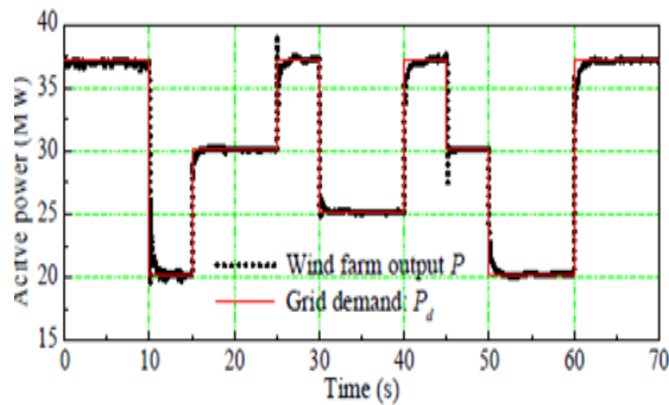


Figure 10: shows the wind farm output without harmonics.

VII CONCLUSIONS

This paper 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. The ESS and the controllers of each individual DFIG wind turbine have been suitably designed. A high-layer WFSC has been developed to coordinate the actions of the low-layer individual WTG controllers. Consequently, the wind farm generates constant active power as required by the grid operator. Simulation studies have been carried out on a wind farm equipped with 15DFIG wind turbines to verify the effectiveness of the proposed CPC scheme. Results have shown that the proposed CPC scheme enabled the wind farm to actively participate in active power regulation of the grid. The proposed system and control scheme provides a promising solution to help achieve high levels of penetration of wind power into electric power grids.

REFERENCES

- [1] "Focus on 2030: EWEA aims for 22% of Europe's electricity by 2030," Wind Directions, pp. 25-34, Nov./Dec. 2006.
- [2] "20% wind energy by 2030: increasing wind energy's contribution to U.S. electricity supply," U.S. Department of Energy, July 2008.
- [3] W. Qiao and R. G. Harley, "Grid connection requirements and solutions for DFIG wind turbines," in Proc. IEEE Energy 2030 Conference, Atlanta, GA, USA, Nov. 17-18, 2008.
- [4] J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy," IEEE Trans. Energy Conversion, vol. 19, no. 2, pp. 441-448, June 2004.
- [5] C. Abbey and G. Joos, "Supercapacitor energy storage for wind energy applications," IEEE Trans. Industry Applications, vol. 43, no. 3, 769-776, May/June 2007.
- [6] A. Yazdani, "Islanded operation of a doubly-fed induction generator (DFIG) wind-power system with integrated energy storage," in Proc. 2007 IEEE Canada Electrical Power Conference, Montreal, Quebec, Oct. 25-26, 2007, pp. 153-159.

ABOUT AUTHORS

Author 1



Syed Abdur Rauf Magrabi received the B.E degree in Electrical and Electronics Engineering from Osmania University, India in 2011 and M.S degree in Microelectronics Engineering from Coventry University, UK in 2013. His research interest includes the design of Smart Grids in Power System Modelling, Artificial Intelligence and Robotics.

Author 2

Shiv Shankar Kumar received B.E degree in Electrical and Electronics Engineering from Osmania Universtiy, 2011 and M.Tech degree in Power Electronics from Sphoorthy Engineering College in 2016. His research interests includes Electrical Machines, Multi-level Inverters and Power Electronics Drives.