INTERNATIONAL RESEARCH JOURNAL IN ADVANCED ENGINEERING AND TECHNOLOGY (IRJAET) E - ISSN: 2454-4752 P - ISSN : 2454-4744
VOL 4 ISSUE 2 (2018) PAGES 3141 - 3155
RECEIVED : 05.03.2018 PUBLISHED : 10.04.2018

April 10, 2018

CONTROL OF DFIG WIND POWER GENERATORS IN AN UNBALANCED MICROGRIDS BASED ON INSTANTAENEOUS POWER THEORY

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Abstract

This paper presents a model and a control strategy for a doubly-fed induction generator (DFIG) wind energy system in an unbalanced micro grid based on instantaneous power theory. The proposed model uses instantaneous real/reactive power components as the system state variables. In addition to the control of real/reactive powers, the controllers use the rotor-side converter for mitigating the torque and reactive power pulsations. The control scheme also uses the grid-side converter for partial compensation of unbalanced stator voltage. The main features of the proposed control method are its feedback variables are independent of reference frame transformations and it does not require sequential decomposition of current components. These features simplify the structure of required controllers under an unbalanced voltage condition and inherently improve the robustness of the controllers. A power limiting algorithm is also introduced to protect power converters against over rating and define the priority of real/reactive power references within the control scheme. The performance of the proposed strategy in reducing torque ripples and unbalanced stator voltage is investigated based on the time-domain simulation of a DFIG study system under unbalanced grid voltage.

Keywords
Conventional Vector Control Scheme, instantaneous power control, unbalanced voltage conditions, wind turbine, Doubly-Fed Induction Generator (Phasor Type), Rotor-Side Converter Control System, Rotor-Side Converter Control System, Grid-Side Converter Control System

Nomenclature

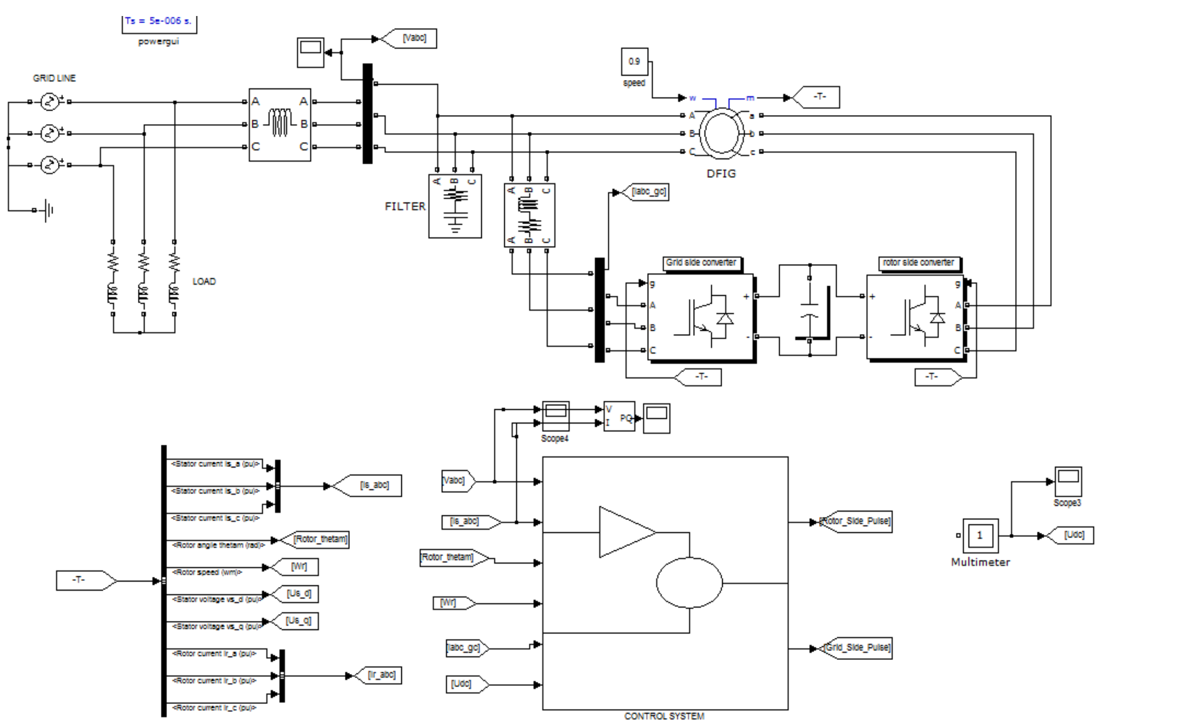
P_m	Mechanical power captured by the wind turbine and transmitted to the rotor
P_s	Stator electrical power output
P_r	Rotor electrical power output
P_{gc}	C_{grid} electrical power output
Q_s	Stator reactive power output
Q_r	Rotor reactive power output
Q_{gc}	C_{grid} reactive power output

T_m	Mechanical torque applied to rotor
T_{em}	Electromagnetic torque applied to the rotor by the generator
ω_r	Rotational speed of rotor
ω_s	Rotational speed of the magnetic flux in the air-gap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles.
J	Combined rotor and wind turbine inertia coefficient
V	Positive sequence voltage (pu)
I	Reactive current (pu/Pnom) (I > 0 indicates an inductive current)
X_s	Slope or droop reactance (pu/Pnom)
Pnom	Three-phase nominal power of the converter specified in the block dialog box
GPs and *GQs*	control scheme of two controllers,
KrpsGres, *KrqsGres*	double-frequency torque
and *KrTeGres*	reactive power pulsations
Krps, *Krqs* and *KrTe*	constant gains
Gres	band pass filter tuned at double frequency

1. INTRODUCTION

A huge amount of doubly-fed induction generators (DFIGs) in high-power wind turbine generators (WTGs) are operational as distributed generators (DGs) units in micro grids. Recent grid codes require a WTG remains operational during transient and steady-state unbalanced grid voltages . A voltage unbalance can steadily exist in a micro grid due to unequal impedance of distribution lines; nonlinear loads such as arc furnaces; and unequal distributions of single-phase loads. Propose a distributed intelligent residential load transfer scheme to dynamically reduce voltage unbalance along low voltage distribution feeders. However, due to using widely distributed and variable loads such as single-phase motors and nonlinear loads in a micro grid, the voltage unbalance condition cannot be completely mitigated. On the other hand, even a small amount of voltage unbalance can cause notable current unbalance in a DFIG. This current unbalance causes torque pulsations and overheating of the machine windings which eventually reduce the lifetime of a DFIG-based WTG in a micro grid .Modeling and vector control of DFIG-based wind turbine under unbalanced conditions in micro grids are widely addressed in literature . The existing unbalanced vector control schemes for DGs conventionally use two pairs of individual controllers for the positive and negative sequence components of unbalanced currents

.Tuning of these controllers due to the delays of the decomposing positive/negative sequences filters often requires complex algorithms in unbalanced vector control schemes .Alternative methods have been introduced which directly process the unbalanced rotor current without decomposition into positive/negative sequences. However, in these methods, the calculation of current references based on the power pulsations also requires the positive and negative sequence components of the machine stator voltage, current, and flux. Direct power control (DPC) methods have been also suggested for unbalanced voltage condition which relatively reduce the complexity of the control method compared to the vector control scheme . However, the DPC methods similar to the unbalanced vector control methods still need decomposition of positive/negative sequences and compensation for the filters delays. This paper presents a control method for a DFIG connected to an unbalanced grid voltage, which uses the instantaneous real/reactive powers as the state variables. The proposed control approach offers a robust structure since its state variables are independent of the positive/negative sequences of the DFIG current components. The suggested control scheme also reduces the DFIG torque/power pulsations by using the real/reactive power commands of the rotor-side converters in a DFIG wind energy system. Furthermore, at low wind speed and high unbalanced grid voltage conditions, the excess capacity of grid-side converter can be used for partial compensation of unbalanced stator voltage. Two current/power limiting algorithms are also introduced for both rotor- and grid-side converters to avoid over rating of the converters. The performance of the proposed method under unbalanced grid voltage condition is investigated via time-domain simulation of a MW-scale DFIG wind turbine-generator study system in which a single-phase load is used to impose a steady voltage unbalance to the micro grid.



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2. CONVENTIONAL VECTOR CONTROL SCHEME FOR DFIG SYSTEM UNDER UNBALANCED CONDITION

The schematic diagram of a DFIG WTG including rotor-side (RSC) and grid-side (GSC) converters. Under balanced voltage condition, the converter controller scan be designed based on conventional vector control or other design techniques such as resonance controller and direct power control using instantaneous power model of the DFIG . However, under unbalanced voltage condition, auxiliary control loops using negative sequences quantities must be added to the conventional vector speed controllers which form an extended unbalanced vector control
Scheme. .Figure.2 shows details of the unbalanced vector control scheme for the rotor-side converter.

This control strategy mitigates the torque pulsations and the grid unbalanced effects on the generator via independent control of the stator real/reactive power components, *ps* and *qs* .The sequential decomposition unit in Fig. 2 calculates the positive/negative sequence components in positive/negative sequence *qd* reference frame. The outputs of this unit are denoted by *f+/−+/−* where *f* represents the voltage or current quantities; superscripts identify +/- sequence reference frame; and subscripts represent +/- sequence components. In Fig. 2,the +/- reference frame transformations are realized by *e j(θs−θr)*and *ej(−θs−θr)*.As shown in Fig. 2, the unbalanced vector control method is established based on decomposition of the positive and negative sequences of the rotor current. Practically, this decomposition can be realized by transferring the current to the synchronous reference frame and using digital filters, or signal delay cancelation technique. These methods introduce time delays and obvious errors in amplitude and phase which adversely affect on the dynamic performance of the control system .Recently, alternative methods such as the Proportional Integral Resonant (PIR) controller and the main and auxiliary controllers have been introduced which directly process the unbalanced rotor current without decomposition into positive/negative sequences. In these methods, the current references are calculated according to the power pulsations in a feed-forward manner so the stator voltage, current, and flux have to be decomposed into the positive and negative sequences for calculating the rotor current.

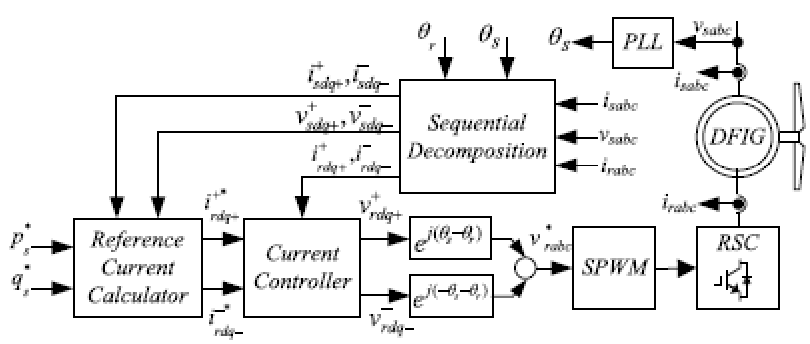

Fig. 2. Schematic diagram of the conventional unbalanced vector control scheme for DFIG [12], [13].

3. PROPOSED INSTANTANEOUS POWER CONTROL FOR UNBALANCED VOLTAGE CONDITIONS

In the proposed method, the rotor-side converter in Fig. 1can be used for the mitigation of the torque and stator reactive power pulsations. Also, the grid-side converter can be used for reduction of unbalanced stator voltage. In the proposed control method, the feedback loops are developed based on instantaneous real/reactive power components which can be directly calculated in *abc* frame and used in any other reference frame

Mitigation of Torque/Reactive Power Pulsations Using RSC

Although GSC to some extent can compensate the unbalanced grid voltage, the torque and power pulsations still exist due to $2\omega e$ ripple which superimposed on the dc-link voltage.The torque pulsation in a generator increases stress on the rotating shaft of the DFIG which can cause shaft fatigue or other mechanical damages to a WTG. Thus, a control provision is required for the rotor-side converter to mitigate the torque/power pulsations of DFIG. That the simultaneous elimination of the torque and real power pulsations cannot be performed under unbalanced grid voltage condition. Thus, the proposed control scheme herein is designed to compensate the torque and reactive power pulsations. This control scheme essentially consists of two controllers, *GPs* and *GQs*, which are designed for a balanced condition as discussed. Then, extra feedback control loops including *KrpsGres, KrqsGres* and *KrTeGres* are added to compensate the double-frequency torque and reactive power pulsations without decomposing the positive and negative sequences of currents and voltages. The *Krps, Krqs* and *KrTe* are constant gains and *Gres* is a band pass filter tuned at double frequency. The electric torque can be estimated by stator and rotor current components in the stationary reference frame as

$$T_e = \frac{3PL_m}{2}\left(i_{sQ}i_{rD} - i_{sD}i_{rQ}\right).$$

4. WIND TURBINE

Wind power is taking off in a big way worldwide, in both giant utility-scale installations and small-scale turbines intended to power a single home. Remote off-grid dwellers are finding wind power an excellent supplement to solar during cloudy weather, and enjoying the extra freedom that more power input gives, especially after dark or during cloudy weather. On-grid folks are installing home wind turbines to offset rising power costs, and even selling extra power back to the utility. Judging from the volume of questions I receive about wind power, there are many misconceptions amongst people out in the real world. Even though the physical laws and formulas governing wind power have been well understood for over 150 years, it has taken new fears about falling oil production, rising gas prices, and global climate change to generate the growing interest in wind power we have now with the general public. In this first article of the series, I'll attempt to explain the basics of how power is extracted from the wind, to help readers understand how much power they could expect from turbines of different sizes. Future parts of this series will cover many other small wind topics.

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Wind Turbines Work

A wind turbine extracts energy from moving air by slowing the wind down, and transferring this harvested energy into a spinning shaft, which usually turns an alternator or generator to produce electricity. The power in the wind that's available for harvest depends on both the wind speed and the area that's swept by the turbine blades.

A. Horizontal Axis Turbines

Horizontal axis turbines are the most common turbine configuration used today. They consist of a tall tower, atop which sits a fan-like rotor that faces into or away from the wind, a generator, a controller, and other components. Most horizontal axis turbines built today are two-or three-bladed. Horizontal axis turbines sit high atop towers to take advantage of the stronger and less turbulent wind at 100 feet (30 meters) or more aboveground. Each blade acts like an airplane wing, so when wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, which causes the rotor to turn. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft spins a generator to make electricity..

B. Vertical Axis Turbines

Vertical axis turbines are of two types: Savonius and Darrieus. Neither type is in wide use. The Darrieus turbine was invented in France in the 1920s. Often described as looking like an eggbeater, it has vertical blades that rotate into and out of the wind. Using aerodynamic lift, it can capture more energy than drag devices. The Giromill and cycloturbine are variants on the Darrieus turbine.

The Savonius turbine is S-shaped if viewed from above. This drag-type turbine turns relatively slowly but yields a high torque. It is useful for grinding grain, pumping water, and many other tasks, but its slow rotational speeds are not good for generating electricity.

In addition, windmills are still used for a variety of purposes. Windmills have been used by humans since at least 200 B.C. for grinding grain and pumping water. By the 1900s, windmills were used on farms and ranches in the United States to pump water and, later, to produce electricity. Windmills have more blades than modern wind turbines, and they rely on drag to rotate the blades.

Wind power is one of the oldest renewable technologies.

- As wind speed doubles, power generation capability increases eightfold
- Higher is better: hilltops and tall towers lead to greater energy production
- Unlike fossil fuels, wind power cannot be depleted and produces no pollution

Humans have been harnessing the wind ever since farmers in ancient Persia figured out how to use wind power to pump water. Wind power turns the kinetic energy of the wind into mechanical or electrical power than can be used for a variety of tasks. Whether the task is creating electricity or pumping water, the wind offers an inexpensive, clean and reliable form of power. Wind farms are now part of the Texas landscape with 187 megawatts (MW) installed.

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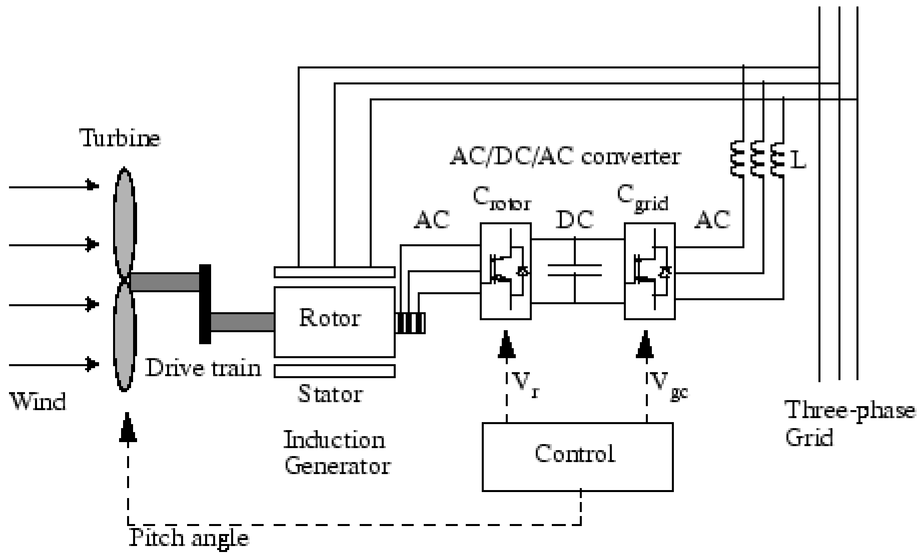
5. WIND TURBINE DOUBLY-FED INDUCTION GENERATOR (PHASOR TYPE)

The Wind Turbine and the Doubly-Fed Induction Generator System

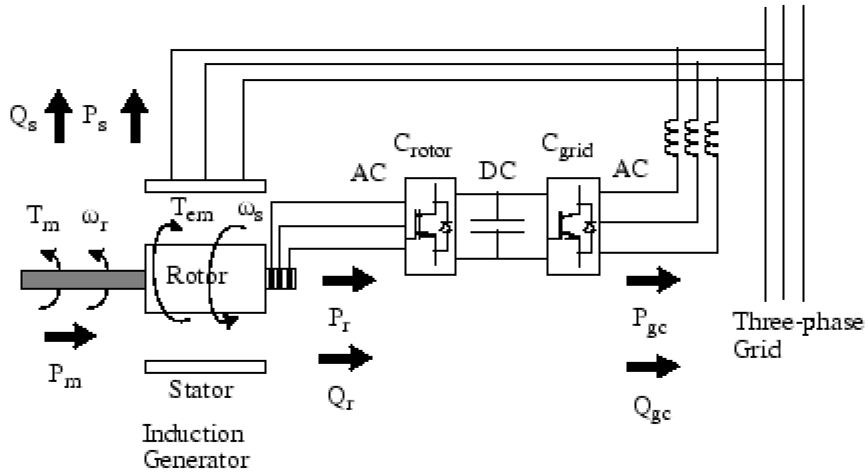


The AC/DC/AC converter is divided into two components: the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). C_{rotor} and C_{grid} are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor L is used to connect C_{grid} to the grid. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals V_r and V_{gc} for C_{rotor} and C_{grid}respectively in order to control the power of the wind turbine, the DC bus voltage, and the reactive power or the voltage at the grid terminals.

Operating Principle

Power flow, as illustrated in the figure, describes the operating principleof the Wind Turbine Doubly-Fed Induction Generator.

The Power Flow



The mechanical power and the stator electric power output are computed as follows:

The parameters for the power flow figure are

$$P_m = T_m\omega_r P_s = T_{em}\omega_s.$$

For a lossless generator the mechanical equation is:

$$J\frac{d\omega_r}{dt}=T_m-T_{em}.$$

In steady-state at fixed speed for a lossless generator$T_m = T_{em}$ and $P_m = P_s + P_r$.

It follows that:

$$P_r=P_m-P_s=T_m\omega_r-T_{em}\omega_s=-T_m\frac{\omega_s-\omega_r}{\omega_s}\omega_s=-sT_m\omega_s=-sP_s,$$

where s is defined as the slip of the generator: $s = (\omega_s-\omega_r)/\omega_s$.

Generally the absolute value of slip is much lower than 1 and, consequently, P_r is only a fraction of P_s. Since T_m is positive for power generation and since ω_s is positive and constant for a constant frequency grid voltage, the sign of P_r is a function of the slip sign. P_r is positive for negative slip (speed greater than synchronous speed) and it is negative for positive slip (speed lower than synchronous speed). For super-synchronous speed operation, P_r is transmitted to DC bus capacitor and tends to rise the DC voltage. For subsynchronous speed operation, P_r is taken out of DC bus capacitor and tends to decrease the DC voltage. C_{grid} is used to generate or absorb the power P_{gc} in order to keep the DC voltage constant. In steady-state for a lossless AC/DC/AC converter P_{gc} is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by C_{rotor}. The power control is explained below.

The phase-sequence of the AC voltage generated by C_{rotor} is positive for subsynchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. C_{rotor} and C_{grid} have the capability of generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals.

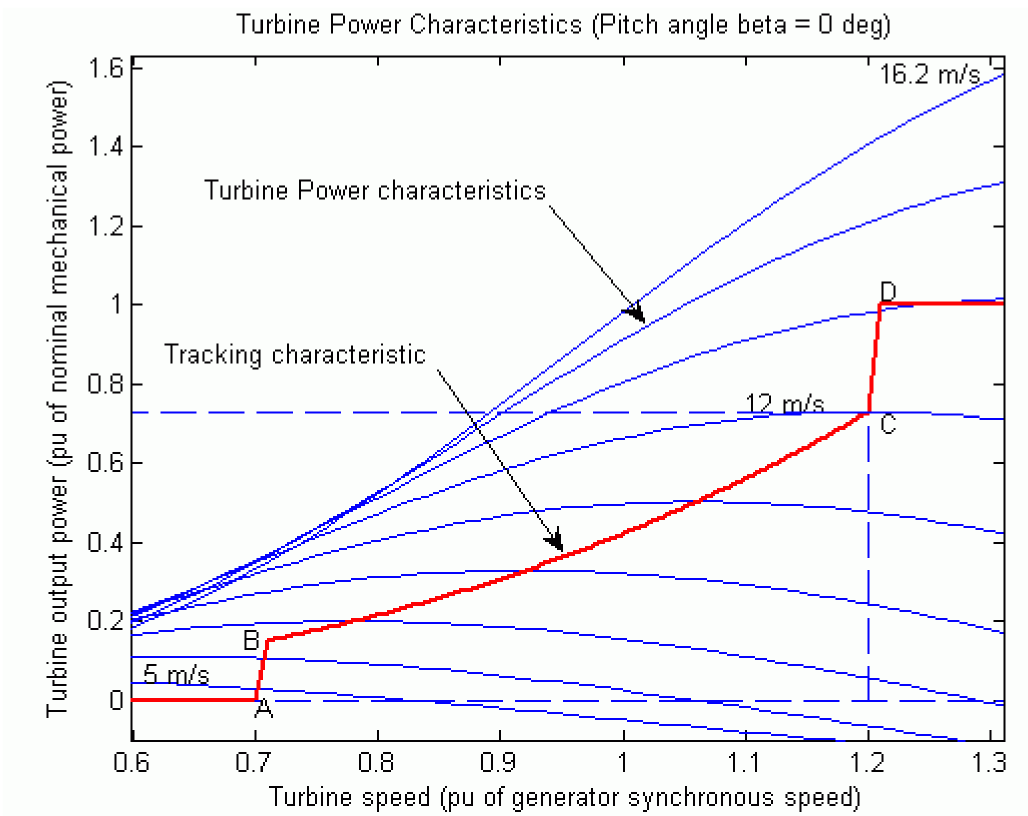
C_rotor Control System

The rotor-side converter is used to control the wind turbine output power and the voltage (or reactive power) measured at the grid terminals.

Power Control

The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. An example of such a characteristic is illustrated by the ABCD curve superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds.

6. TURBINE CHARACTERISTICS AND TRACKING CHARACTERISTIC



The actual speed of the turbine ω_r is measured and the corresponding mechanical power of the tracking characteristic is used as the reference power for the power control loop. The tracking characteristic is defined by four points: A, B, C, and D. From zero speed to speed of point A, the reference power is zero. Between point A and point B the tracking characteristic is a straight line, the speed of point B must be greater than the speed of point A. Between point B and point C the tracking characteristic is the locus of the maximum power of the turbine (maxima of the turbine power versus turbine speed curves). The tracking characteristic is a straight line from point C and point D. The power at point D is one per unit (1

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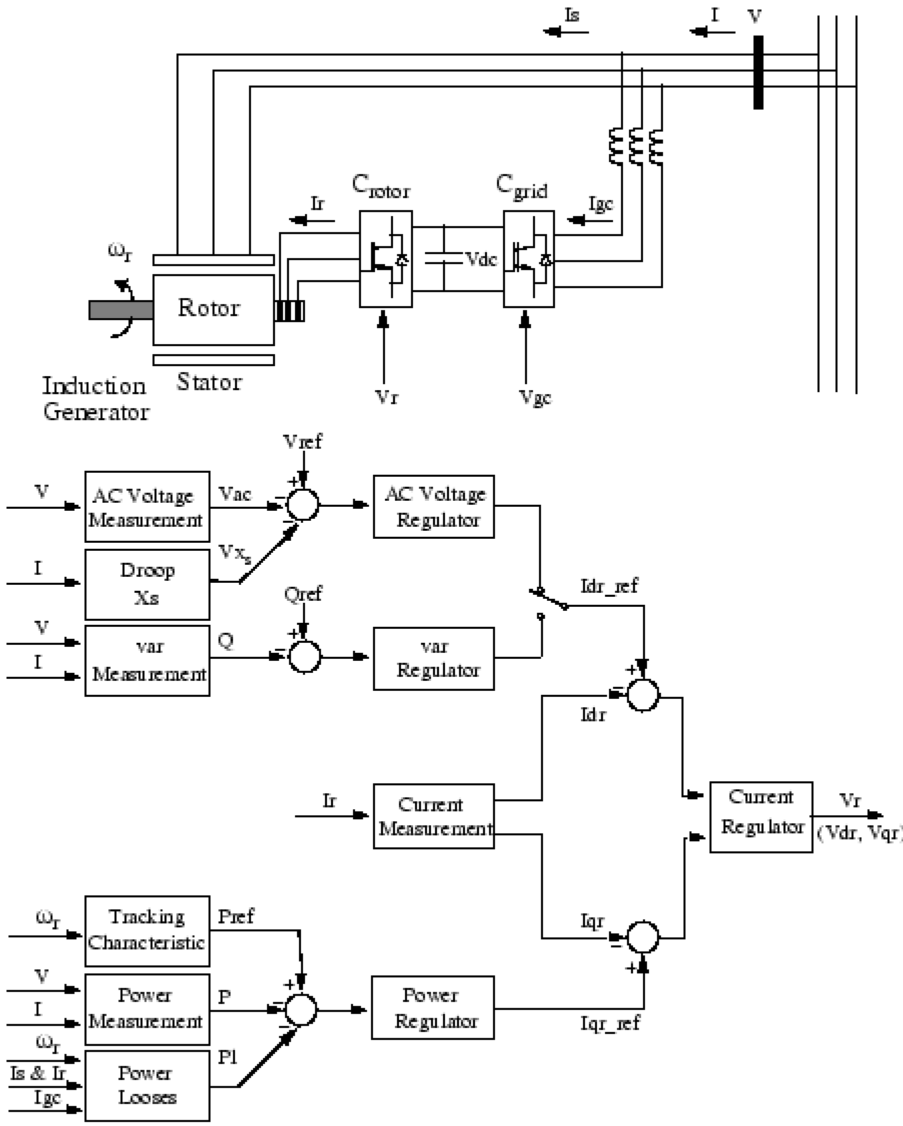
pu) and the speed of the point D must be greater than the speed of point C. Beyond point D the reference power is a constant equal to one per unit (1 pu).

The generic power control loop is illustrated in the figure.

A. Rotor-Side Converter Control System

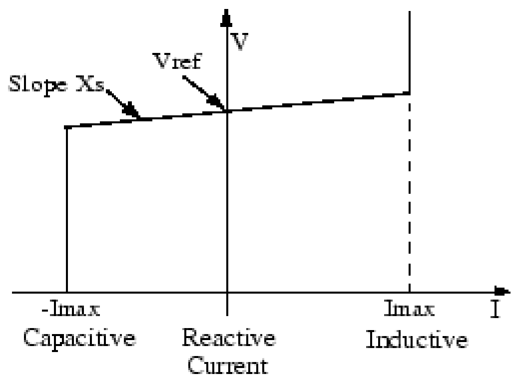


The actual electrical output power, measured at the grid terminals of the wind turbine, is added to the total power losses (mechanical and electrical) and is compared with the reference power obtained from the tracking characteristic. A Proportional-Integral (PI) regulator is used to reduce the power error to zero. The output of this regulator is the reference rotor current Iqr_ref that must be injected in the rotor by converter C_{rotor}. This is the current component that produces the electromagnetic torque T_{em}. The actual Iqr component of positive-sequence current is compared to Iqr_ref and the error is reduced to zero by a current regulator (PI). The output of this current controller is the voltage Vqr generated by C_{rotor}. The current regulator is assisted by feed forward terms which predict Vqr.

B. Voltage Control and Reactive Power Control

The voltage or the reactive power at grid terminals is controlled by the reactive current flowing in the converter C_{rotor}. The generic control loop is illustrated in the figure.

7. WIND TURBINE V-I CHARACTERISTIC



When the wind turbine is operated in voltage regulation mode, it implements the following V-I characteristic.

As long as the reactive current stays within the maximum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the indicated slope. In the voltage regulation mode, the V-I characteristic is described by the following equation:

$$V = V_{ref} + X_s I,$$

When the wind turbine is operated in var regulation mode, the reactive power at grid terminals is kept constant by a var regulator.

The output of the voltage regulator or the var regulator is the reference d-axis current Idr_ref that must be injected in the rotor by converter C_{rotor}. The same current regulator as for the power control is used to regulate the actual Idr component of positive-sequence current to its reference value. The output of this regulator is the d-axis voltage Vdr generated by C_{rotor}. The current regulator is assisted by feed forward terms which predict Vdr.

Vdr and Vqr are respectively the d-axis and q-axis of the voltage Vr.

Note:

- for C_{rotor} control system and measurements the d-axis of the d-q rotating reference frame is locked on the generator mutual flux by a PLL which is assumed to be ideal in this phasor model.

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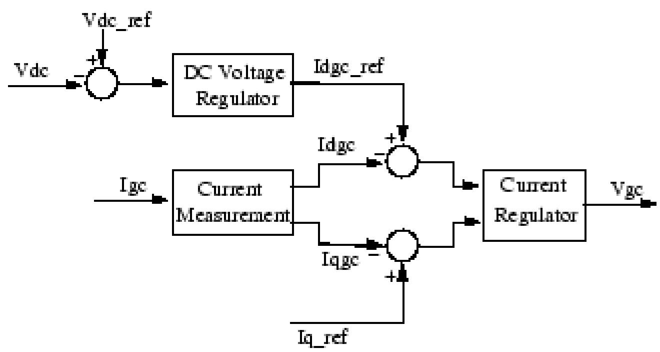
- the magnitude of the reference rotor current Ir_ref is equal to $GI_{2dr\_ref}{}^{+}I_{2qr\_ref}$. The maximum value of this current is limited to 1 pu. When Idr_ref and Iqr_ref are such that the magnitude is higher than 1 pu, the Iqr_ref component is reduced in order to bring back the magnitude to 1 pu.

C_grid Control System

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 is llustrated in the figure.

Grid-Side Converter Control System



The 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 Vdc.
- An outer regulation loop consisting of a DC voltage regulator. The output of the DC voltage regulator is the reference current Idgc_ref for the current regulator (Idgc = 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} (Vgc) from the Idgc_ref produced by the DC voltage regulator and specified Iq_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 Igc_ref is equal to

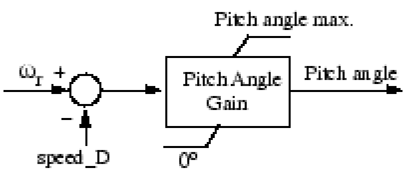
$$GI_{2dgc\_ref}{}^{+}I_{2qr\_ref}$$

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

Pitch Angle Control System

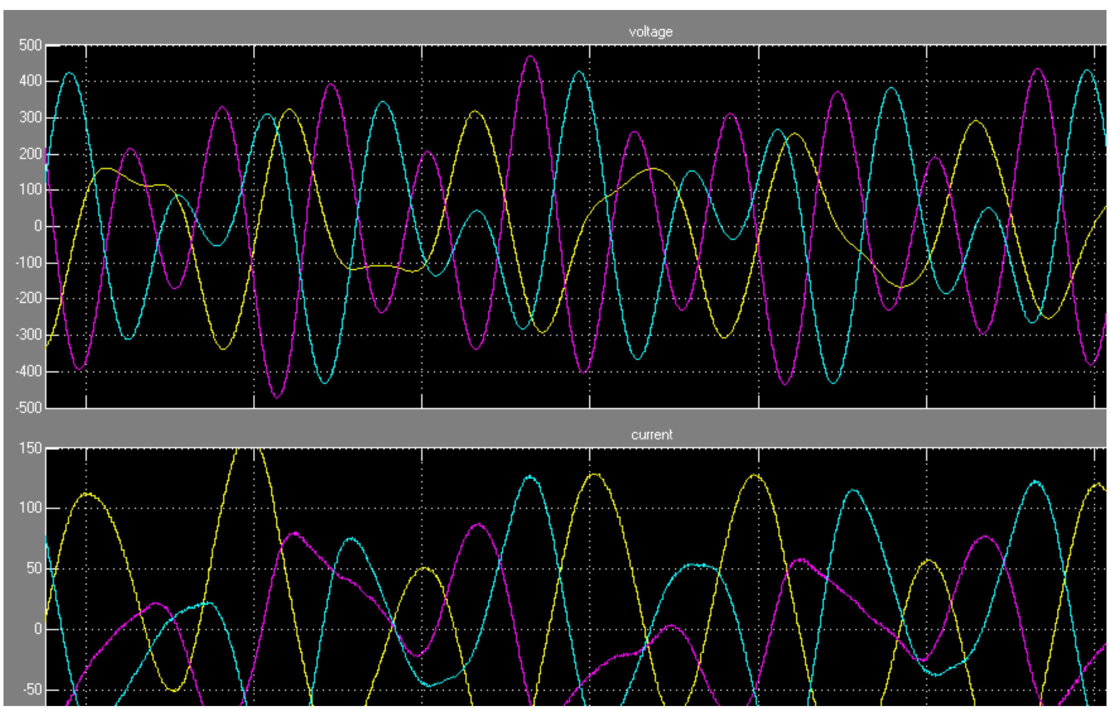
The pitch angle is kept constant at zero degrees until the speed reaches point D speed of the tracking characteristic. Beyond point D the pitch angle is proportional to the speed deviation from point D speed. The control system is illustrated in the following figure.

Pitch Control System



8. SIMULATION OUTPUT ANALYSIS

To analyse impact control strategy for a doubly-fed induction generator (DFIG) wind energy system in an unbalanced micro grid based on instantaneous power theory. The proposed model uses instantaneous real/reactive power components as the system state variables. In addition to the control of real/reactive powers, the controllers use the rotor-side converter for mitigating the torque and reactive power pulsations. The control scheme also uses the grid-side converter for partial compensation of unbalanced stator voltage. The main features of the proposed control method are its feedback variables are independent of reference frame transformations and it does not require sequential decomposition of current components. These features simplify the structure of required controllers under an unbalanced voltage condition and inherently improve the robustness of the controllers.



A. Disadvantages

1. Solar energy weather dependent.

2. The initial cost of purchasing a solar and wind system is fairly high

3. The more electricity you want to produce, the more solar panels you will need because you want to collect as much sunlight as possible.

4. Wind farms are noisy and may spoil the view for people living near them. The amount of electricity generated depends on the strength of the **wind -** if there is no **wind**, there is no electricity.

B. Advantage

- As the world moves towards renewable energy generation and acts to counter climate change, micro grids offer a range of benefits which can provide assistance both locally and nationally in terms of the environmental benefits.
- Reduced Electricity Bill
- Diverse application
- Low maintenance cost
- **Wind** is a **renewable energy** resource and there are no fuel costs. ...

CONCLUSION

An unbalanced control scheme for a DFIG wind turbine generator has been presented in this paper which does not require the sequential decomposition of the DFIG stator/rotor currents and is less sensitive to the system parameters. This control scheme mitigates the stator reactive power and torque pulsations which obviously appear in any balanced control scheme under an unbalanced grid voltage condition. The control method uses the grid-side converter to partially compensate the unbalance stator voltage when the wind speed is low and turbine works below nominal power. Two current/power limiting algorithms are also introduced for both rotor- and grid-side converters to avoid over rating of the converters. It has been shown that proposed control approach based on its simple and robust structure can offer a promising solution for DFIG control under unbalanced grid voltage conditions.

ACKNOWLEDGEMENT

The author’s acknwedge the management of SCSVMV University, Kanchipuram Tamilnadu, India. And head of the department Of Electrical And Electronics Engineer, for the support and keen interest in promoting the research and development in the division by providing the facilities

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