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Control of doubly-fed induction generator, revisited

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Abstract--Most of today's commercial wind turbines are equipped with doubly fed induction generator (dfig) because of the advantages it offers. Many techniques have been proposed for the control of this class of wind turbine, some of which may be impracticable due to a large volume of required real time computations involved in their implementation. Thus, the subject is open to new ways of more efficient control strategies. In this paper a new way of looking at the control problem is studied based on the nature of how these machines work and how a controller manipulates their operation. The advantage is that a control scheme can be designed offline, and the results can then be implemented in a table-lookup. This is more suitable in practice. In an example some preliminary simulation results demonstrate the principle of this strategy.

Index Terms— Wind Power Generation, Control, Induction machine, DFIG

I. INTRODUCTION

Many commercial wind turbines today employ Wound Rotor Induction Machine (WRIM) for the generator, more known as Doubly Fed Induction Generator (DFIG). Although the trend is towards gearless turbines, this generator will continue to be used for many years to come because of its advantages that outweigh its disadvantages. Compared with squirrel cage machine the main advantage is that it can continue generation at a much wider range of wind speeds, at which a cage machine must stop. In addition, a DFIG can behave as a synchronous machine in the sense that the active and reactive power can be independently controlled, thus it is possible to adjust the output power factor. A third advantage is the possibility of torque control, as used in practice by some WT manufacturers. For wind turbines this flexibility allows a much better adaptation to the variation in the wind speed for maximum power harness, or for smoothing out the sudden torque changes experienced by the main shaft.

In industry, control of a turbine is mainly according to the power curve defined for a turbine based on the power capacity of the turbine generator. Part of this control action involves pitching the blades for limiting the power grasp from wind, based on wind speed. This is from the turbine side, and the controller determines the turbine speed. From the generator side, the generator is subject to a variable input speed, and it is necessary to regulate its operation for maximum output, considering the other criteria such as power factor or the shaft torque. This is performed through

controlling the stator and rotor currents. The technique and the details of how it is implemented in any particular turbine is, however, a proprietary of the manufacturer.

In the academia and research community, nonetheless, many control design techniques are proposed for various objectives, such as active power control, reactive power control, torque control and the like. In the literature much has been said about different techniques for formulation of the control problem and regulating the behavior of DFIG. The studies involve many cases of laboratory experimentation [1], [2], [3], [4], or simulation [5], [6], [7]. In a commercial system the safe operation and protection of the system is also of primary importance and the required measurements and actions are embedded with turbine control algorithms.

Most of the control techniques proposed are based on vector control [8], which allows a virtual transformation from 3-phase AC to a virtual DC equivalent for a machine. In this way, two current components are obtained, one for generating torque and the other for generating a magnetic field, similar to a DC machine. The bottom line in all the approaches, as exemplified by the references, is a manipulation of the generator stator and rotor currents.

In this paper, the control strategy is looked at from a different angle. We consider the effect of the action of a controller to the generator, which ultimately boils up to manipulation of the rotor winding current.

II. GOVERNING EQUATIONS

In all analytical work the knowledge about the relationships governing the function of an induction machine is necessary. Figure 1 is helpful for understanding the magnetic relationships, as well as the temporal (phase) relationships between the stator and rotor currents and voltages. The figure corresponds to phasor representation of magnetic flux and currents for one phase of a three-phase machine, but the other phases are repeat of the same thing with a spatial difference. In this figure the vectors denote the instantaneous positions of the maxima of the assumed sinusoidal waveforms of magnetic fluxes and currents. Figure 1 is based on the following relationships and according to [10]

$$\lambda_s = \lambda_m + L_{sl}i_s \quad (1)$$

$$\lambda_r = \lambda_m + L_{rl}i_r \quad (2)$$

On the other hand, when the wind speed is below a certain limit, a dfig runs at sub-synchronous speed and continues generation. Thus, based on the wind speed a dfig must switch from super-synchronous speed to sub-synchronous and vice versa.

Practically, the common method for allowing taking energy from the rotor winding or delivering energy to it (for sub-synchronous operation) is having power converters. The reason is to change the voltage and frequency of the rotor output to that of the grid, or vice versa.

If the synchronous speed of a machine is N_s rpm and the rotor speed is N_r rpm, then their associated frequencies (in radians per second) are

$$\omega_s = \frac{2\pi N_s}{60} \quad \text{and} \quad \omega_r = \frac{2\pi N_r}{60}$$

and the frequency of the voltage in the rotor winding is

$$\omega_{slip} = \omega_s - \omega_r \quad (12)$$

Then the machine slip is

$$s = \frac{N_s - N_r}{N_s} = \frac{\omega_s - \omega_r}{\omega_s} \quad (13)$$

and the rotor current frequency can also be expressed as

$$\omega_{slip} = \omega_s - \omega_r = \frac{\omega_s - \omega_r}{\omega_s} \times \omega_s = s\omega_s \quad (14)$$

For sub-synchronous operation s is positive and for super-synchronous it is negative.

Since s is small in magnitude (less than 0.03 typically) the rotor winding has a very low frequency. The arrangement for a wind turbine DFIG generator is two back-to-back converters connected together by a capacitor (voltage source) or an inductor (current source). This is schematically depicted in figure 3. Based on the requirement (depending on the wind speed) each converter can function as a rectifier or an inverter, where the other converter does the reverse. In this way, the voltage and frequency of the rotor output can be brought at those of the stator level, or conversely a low frequency AC with the appropriate voltage can be injected to the rotor winding.

Fig. 3 Common implementation of back to back converters with DFIG in wind turbines

Dealing with real values of voltages and currents for the purpose of deriving control schemes or implementing them is cumbersome. For this reason, in order to better manage the equations for torque and power in terms of the applied voltage, frequency and current, a set of two transformations are performed on the measured values of these variables. The first one, called Park, Clarke, or dq0 transform, converts a three-phase system to a virtual two axis system. In this way the induction machine resembles a DC machine in which the field and armature windings can be independently controlled. The coordinates of the two-axis system are commonly called d-axis and q-axis, d referred to as the direct coordinate and q, at 90° CCW from d, as the quadrature coordinate. A second transformation is also necessary for expressing conversion between two coordinate systems with an angle between them. For instance, coordinates attached to rotor and coordinates attached to stator magnetic fluxes, which are not in phase. Details of this transformations are available in the literature and are not discussed here.

After the variables are expressed in dq-coordinates equations governing the relationships between the voltage, current and the developed magnetic flux are

$$v_{sd} = R_s i_{sd} + \frac{d}{dt} \lambda_{sd} - \omega_s \lambda_{sq} \quad (15)$$

$$v_{sq} = R_s i_{sq} + \frac{d}{dt} \lambda_{sq} + \omega_s \lambda_{sd} \quad (16)$$

$$v_{rd} = R_r i_{rd} + \frac{d}{dt} \lambda_{rd} - (\omega_s - \omega_r) \lambda_{rq} \quad (17)$$

$$v_{rq} = R_r i_{rq} + \frac{d}{dt} \lambda_{rq} + (\omega_s - \omega_r) \lambda_{rd} \quad (18)$$

As can be understood, λ_{sd} , λ_{sq} , λ_{rd} and λ_{rq} are the direct and quadrature components of the stator and rotor magnetic flux linkages, respectively. The same definition applies to the d- and q-components of the stator and rotor voltages and currents. R_s and R_r are the stator and rotor winding resistances, respectively.

Furthermore, equations (7) and (8) assume the forms

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd} \quad (19)$$

$$\lambda_{sq} = L_s i_{sq} + L_m i_{rq} \quad (20)$$

$$\lambda_{rd} = L_m i_{sd} + L_r i_{rd} \quad (21)$$

$$\lambda_{rq} = L_m i_{sq} + L_r i_{rq} \quad (22)$$

and the relationships for the electromagnetic torque and power are

$$\tau = \frac{3}{2} p L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad (23)$$

$$P = \frac{3}{2} (v_{sd} i_{sd} + v_{sq} i_{sq}) \quad (24)$$

$$Q = \frac{3}{2} (v_{sq} i_{sd} - v_{sd} i_{sq}) \quad (25)$$

where p is the number of pairs of poles of the machine (stator), P is the active power and Q is the reactive power.

IV. A NEW LOOK TO THE DFIG CONTROL

A closer look at what happens in the control of a doubly fed induction machine reveals that any control action, indeed, is performed by manipulating the rotor current. The rotor current as a result of its natural behavior is a (sinusoidal) waveform with a frequency of ω_{slip} as define by equations (12-14).

No matter what philosophy drives the control scheme for a variable speed turbine with DFIG, we notice that:

- 1- The power to be extracted from the generator at each wind speed is determined based on the turbine power curve.
- 2- How much power is to be taken from the rotor is determined based on a pre-scheduled program by the turbine manufacturer. This is true also for the power to be injected to the rotor in case of sub-synchronous operation.
- 3- The rotational speed of a turbine is determined based on the maximization of the power coefficient, which depends on the wind speed (through tip speed ration), too.
- 4- The frequency of the rotor current/voltage (ω_{slip}) depends on the rotational speed and the synchronous speed; thus, it depends on the wind speed in light of 3.
- 5- The maximum voltage in the rotor winding depends on the generator physical (electrical) properties.
- 6- The actual rotor voltage is proportional to the maximum rotor voltage and approximately changes linearly with slip speed. Thus, depends on the rotor speed, which depends on the wind speed (in light of 3).

From the above facts, it can be seen that the wind speed defines the proper values for various variables, including the current in the rotor winding, which determines the torque on the shaft.

In the super-synchronous operation, the power that is taken from the rotor determines the rotor current. The frequency is not changed by this power taken from the rotor. But it can introduce a phase difference between rotor voltage and rotor current. In the sub-synchronous operation, the power that is injected to the rotor winding can be out of phase with the rotor voltage (depending on firing angle).

The rotor current to be manipulated, thus, has a known frequency ω_{slip} , at each instant of time, as dictated by the wind speed and the gearbox ratio. This manipulation is either injecting a voltage to the rotor winding or taking power from it. Both of these actions imply adding a waveform to the already present waveform of the rotor current. As such, the waveform of the rotor current at a given time can be assumed to be in the form of

$$i_r = A \cos(\omega_{slip} t) \quad (26)$$

and the waveform which is adding to it can be expressed as

$$i_{cont} = B \cos(\omega_{slip} t + \gamma) \quad (27)$$

A and B depend on the machine parameters; B is smaller than A , and preferably equal to A for super-synchronous operation. It can be larger than A for sub-synchronous case. γ is, indeed, the firing angle of the IGBT's (or thyristors) in the back-to-back converters. Then the resultant current in the rotor is a waveform with the same frequency the amplitude of which is modified and has a phase difference with respect to the original rotor current, as it is easy to do the math and observe that

$$i_r + i_{cont} = \frac{A+B \cos \gamma}{\cos \eta} \cos(\omega_{slip} t + \eta) , \quad (28)$$

$$\text{where } \eta = \tan^{-1} \frac{B \sin \gamma}{A+B \cos \gamma}$$

A comparison of equations (26) and (28) indicates that the original rotor current has been multiplied by $\frac{A+B \cos \gamma}{\cos \eta}$ and it is shifted by the angle η .

The relationship between the control signal phase angle γ and the resulting shift in the rotor current η is

$$\gamma = \eta + \sin^{-1} \left(\frac{A}{B} \sin \eta \right) \quad (29)$$

In particular, η is zero if $\gamma = 0$, and $\gamma = 2\eta$ if $B = A$.

Fig. 4. Rotor current (D) as a result of injecting waveform C when original current was waveform A, for $\gamma = 0$

The relationship between rotor current and the induced voltage in the rotor is shown in equations (17) and (18); and equations (21) and (22) reveal that the rotor magnetic flux is affected by both stator and rotor currents. Furthermore, the effect of rotor current on the machine torque is depicted in equation (23). In order to use these relationships, and also equations (24) and (25) for power, it is first necessary to define the frame of reference with respect to which the equations must be expressed. The most common reference frames are those attached to the magnetic flux of the rotor, the stator, or the airgap. It is easy to show that [13] in the frame attached to the airgap

$$i_{sq} + i_{rq} = 0. \quad (30)$$

(This immediately follows from equation (4), as graphically shown in Figure 5.)

In the simulation the vector i_r has been rotated CW (without a change in magnitude) for as far as the power factor can be improved to near unity. Since the rotor current stays constant and the airgap flux is maintained constant according to the discussion for figure 3, the stator current stays constant. Table 1 shows the results for the increments of one degree for η , which corresponds with one degree rotation of i_r . As it can be seen, for each one degree of rotation of i_r , i_s has a larger CCW rotation, as a result of which ϕ_s decreases. The table shows also the values for rotor and stator magnetic fluxes (λ_r and λ_s) and their angles with respect to airgap flux λ_m .

VI. SUMMARY

This paper considers a new way of implementing control action to a doubly fed induction generator in wind turbines. The analysis is based on the fact that for the control of this class of induction machines the rotor winding is manipulated by either taking current from it or injecting current to it, depending on the wind speed and machine characteristics. This fact suggests that instead of real time calculations for direct control, the control strategy can be based on observing the effect of various currents injected to the rotor, for any given situation defined by the wind speed and other associated information. This approach can be implemented through a table look-up, which is more convenient from a practical viewpoint.

Some results are shown by simulation for power factor correction, using this approach to an exemplified machine.

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