Chapter - 7

Steady-State Operation for DFIG

7.1 Introduction

The DFIG model, which has been developed using PSCAD in Chapter 6, is simulated for different control strategies under steady-state conditions and results are presented in this chapter. A wind turbine creates mechanical torque on a rotating shaft, while an electrical generator coupled on the same shaft is controlled to produce an opposing electromagnetic torque. In steady-state operation of a generator, the kinetic energy is converted into electrical energy and is delivered to the grid [62].

In modern wind turbine generators, control plays a very important role. A proper control enables a better use of turbine capacity. In case of a large size of WTG, control of the power quality is required to reduce the adverse effects on their integration into the grid. The poor control may result into voltage variations, additional reactive power consumption, flickering, harmonics and variation in power flow. Therefore it necessitates the study of steady-state as well as transient conditions.

It has been explained in Chapter 5 that PWM frequency converter (back-to-back connected converter) operates as an interface between the rotor windings and the AC grid. This scheme offers independent control of active and reactive powers. Grid-side converter not only controls the DC link voltage, it can also be controlled to consume or produce reactive power. However the apparent power that the converter can manage is limited by its power rating. Rotor-side converter controls the rotor currents in magnitude and phase [13].

A 2.2 MVA, 13.8 kV (Line to Line) doubly-fed induction generator is used in the simulations. The machine parameters are listed in appendix. The schematic of the DFIG to simulate under steady-state condition is shown in Figure 7.1. The wind speed is assumed to be constant during all the simulations presented in this thesis.
7.2 Control of Active power

It has been discussed in Chapter 4 that the three-phase sinusoidal voltage and currents can be depicted as vectors and can be resolved into orthogonal components in phase and in quadrature with the stator magnetic field. Vector control method transforms rotor currents into two parallel controllers, one for the $q$ -component and other $d$ -component. The stator flux rotating synchronously with grid voltage is aligned with the d-axis and equations (4.20) and (4.21) indicate that $q$ - component of the rotor current is used to control the active power, while the $d$ - component is used to control the reactive power.

To investigate the control of active power under steady-state conditions, initially the active and reactive power references are adjusted approximately to 2.2 MW and zero respectively, by adjusting the $i_{qr}$ and $i_{dr}$. The machine is run at super-synchronous condition (1.2 p u). A step increment in $i_{qr}$ is applied at 2s and is held constant for the remaining period of simulation. The simulation in Figure 7.2 shows that the active power ($P_{gen}$) is changed, but there is no appreciable change in reactive power ($Q_{gen}$). This confirms the theoretical decoupled control of $i_{qr}$ as discussed in Chapter 4.
As the active power output is increased with an increase in $i_{qr}$, the corresponding stator and rotor output currents also increase, which is confirmed in Figure 7.3.
7.3 Control of Reactive Power

The reactive power exchanged with the grid at stator terminals is dependent on the direct component of the rotor currents. It also depends on the control of the grid-side converter feeding the rotor-side. Normally the reactive power is adjusted to zero, which means that the grid-side converter operates at unity factor. It has been explained in Chapter 6 that the generator is fully decoupled from the grid by the power converter; therefore the power factor of the generator does not affect the reactive power factor at the grid connection [6].

It is mentioned in equation (4.21) that reactive power can be controlled by decoupled component $i_{dr}$ of the rotor currents. The model is simulated to investigate the control of reactive power by applying a step change in $i_{dr}$ at 2s and is held constant for the remaining part of simulation. The simulation result confirms (Figure 7.4) that a change in $i_{dr}$ controls the reactive power while the active power remains unchanged.

![Figure 7.4](image)

**Figure 7.4** Effect of change in $i_{dr}$. 
7.4 Effect of change in slip

In order to extract the maximum power from the wind, the rotor speed of DFIG should vary with change in wind speed so that it maintains an optimal tip speed ratio $\lambda_t$. The variable speed of the DFIG makes it possible to adjust its speed and hence controls the tip speed ratio. This feature offers the optimal power efficiency co-efficient $C_p$. At the same time the bidirectional power converter should adjust the rotor frequency according to equation (4.23) to keep constant frequency at the stator.

In this section, attempts have been made to study the effects on various parameters for a change in speed. The system is simulated for a change in speed. The speed is changed from sub-synchronous (0.8 pu) to super-synchronous (1.2 pu) speed at about 2s. The Figure 7.5 confirms the transition between the two speeds.

![Figure 7.5](image)

**Figure 7.5** Change in speed from sub-synchronous to super-synchronous speed
In DFIG, the electrical rotor power output $P_r$ is positive for negative slip (super-synchronous speed) and is negative for positive slip (sub-synchronous speed) as explained in Section 4.3. This means that, below the synchronous-speed, the rotor-side power $P_r$ flows from the grid to the rotor of the DFIG, whereas at super-synchronous speed, it flows in the opposite direction. Therefore when the speed was changed from sub-synchronous to super-synchronous speed, it resulted in reversal of rotor output power. The change in the active power $P_{ro}$ and reactive power $Q_{ro}$ in rotor circuit are verified in Figure 7.6.

![Figure 7.6](image)

**Figure 7.6** Rotor power flow from sub-synchronous to super-synchronous speed

Moreover when the speed changes from sub-synchronous to super-synchronous mode or vice-versa, the slip of the machine also reverses according to equation (4.14). Therefore when slip is changed from sub-synchronous to super-synchronous speed, the reversal in the phase-sequence of the rotor currents is observed (Figure 7.7). However, it can be noticed that the phase-sequence of the stator currents remains same, as it is independent of slip of the machine.
In order to achieve the independent control of the active and reactive power flowing between the grid and converter, stator flux vector is aligned with \( d \)-axis. Therefore an important step is to obtain the instantaneous position of the rotating flux in space in order to obtain the rotating reference frame. The angle \( \phi_s \) gives the instantaneous location of the stator’s rotating magnetic field. This is obtained based on three-phase to two-phase transformation and is modeled in Section 4.3. The simulation is shown in Figure 7.8.
The model is also simulated for sub-synchronous and super-synchronous speeds. The responses of the various parameters can be observed in Figures 7.9 and 7.10 for sub-synchronous speed. It is observed in the Figure 7.9 that the active power (P-Gen) is supplied from the stator to the grid. At this point the reactive power (Q-Gen) supplied by the stator is very less. However, the rotor power flow is negative at sub-synchronous speed showing that the power is drawn into the generator from the source as observed in Figure 7.10. It means that the converter is feeding power into the rotor circuit.

**Figure 7.9**  Simulation at sub-synchronous speed

**Figure 7.10**  Simulation at sub-synchronous speed
The simulation results for super-synchronous speed are shown in Figure 7.11. It can be seen that the active power is positive meaning that power is supplied from the stator while the rotor power is also positive i.e. the rotor power is also fed into the grid system. In this condition, the reactive power is controlled to a very low value.

![Simulation at super-synchronous speed](image)

**Figure 7.11** Simulation at super-synchronous speed

Finally the behaviour of the DC link capacitor was studied under steady-state operation. The main task of the grid-side converter is to maintain the DC link voltage. It is concluded that the rotor power $P_r$ is transmitted to DC bus capacitor and it tends to raise the DC voltage for super-synchronous speed. For sub-synchronous speed, $P_r$ is taken out of the DC bus capacitor and tends to decrease the DC voltage. During super-synchronous or sub-synchronous speed, the grid-side converter generates or absorbs the power in order
to keep the DC voltage constant. The DC link voltage remained constant at 7.5 kV during the simulation and is shown in Figure 7.12.

![Figure 7.12](image)

**Figure 7.12**  Constant DC link voltage

### 7.5 Summary

In this chapter, DFIG model developed in the previous chapter is utilised to investigate certain aspects of steady-state operation. The nature of real and reactive powers in stator and rotor circuits of doubly-fed induction generator has been investigated under decoupled control. These findings suggest that vector control can optimise the output of DFIG and speed could be controlled to match the wind velocity. The real and reactive powers generated are also controlled independently. The simulations show that the developed model is also functioning satisfactorily under the super-synchronous speed and sub-synchronous speed of the DFIG. This feature of independent control of reactive power can be used for improving the power quality of the grid.