INTERLEAVED INERTIAL SUPPORT OF WIND TURBINES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

Yazar Ad Soyad

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
COMPUTER ENGINEERING

JUNE 2018

Approval of the thesis:

INTERLEAVED INERTIAL SUPPORT OF WIND TURBINES

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ABSTRACT

INTERLEAVED INERTIAL SUPPORT OF WIND TURBINES

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June 2018, 19 pages

Abstract

Keywords: Keyword1, Keyword2...

ÖZ

BAŞLIK

Duymaz, Erencan
Yüksek Lisans, Bilgisayar Mühendisliği Bölümü
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Özet Türkçe

Anahtar Kelimeler: AnahtarKelime1, AnahtarKelime2...

İthafen...

ACKNOWLEDGMENTS

Teşekkür edilecekler

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DFIG	Doubly Fed Induction Generator
PMSG	Permanent Magnet Synchronous Generator

CHAPTER 1

INTRODUCTION

1.1 Global Renewable Energy Status

Renewable energy is still one of the hottest topics in the power area. The share of the renewable energy systems has been reached significant levels. At the end of 2016, the renewable power capacity has reached 2011 GW throughout the world including hydropower plants.[1] The renewable capacity for the leading countries is given in the Figure 1.1.Almost half of this capacity belongs to four leading countries namely; China, USA, Brazil and Germany. Figure 1.2 shows the energy production from

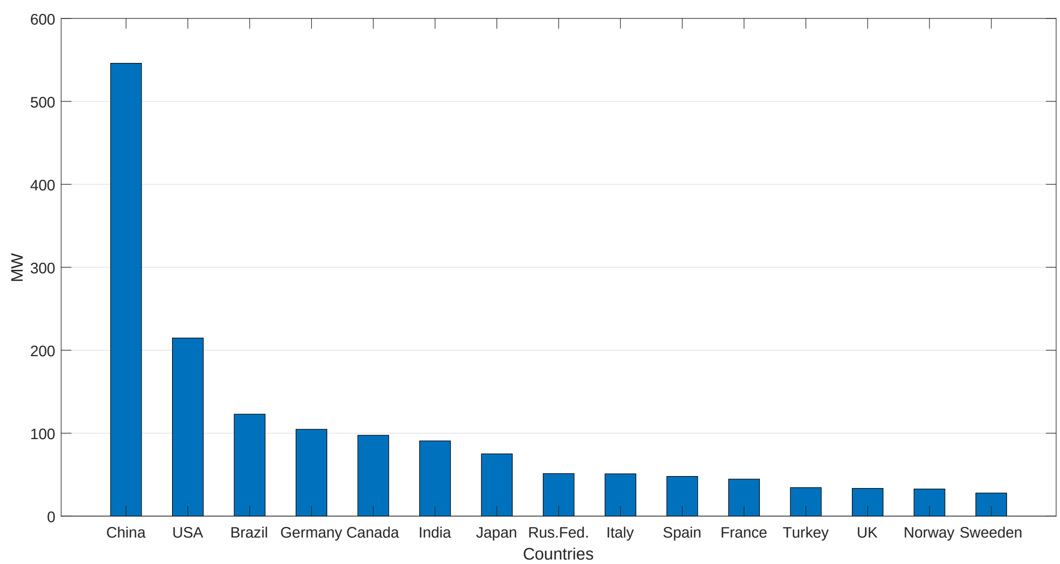


Figure 1.1: Installed Renewable Energy Capacity of Leading Countries in 2016[1]

renewable energy systems. It is clear that China, USA and Brazil produces highest amount of energy from renewable since they already have the highest installed capacity. However, India and Canada produces more energy than Germany even though

Germany has more installed capacity. This result is due to the fact that renewable energy system production is dependent on parameters such as solar radiation and wind speed depending on the renewable source.

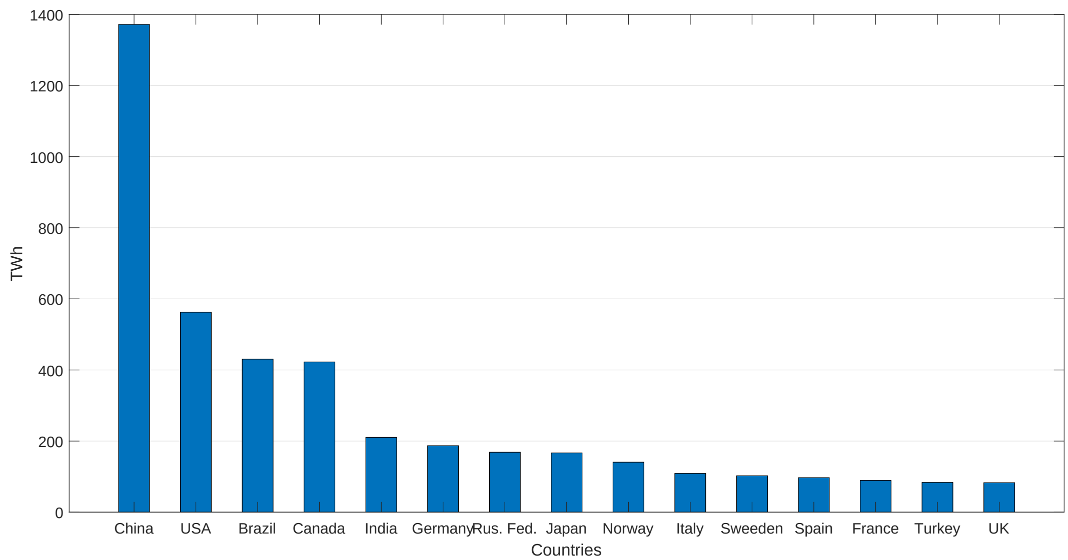


Figure 1.2: Renewable Energy Production of Leading Countries in 2016 [1]

1.1.1 EU 2020 Goals

In 2008, 20 20 by 2020-Europe's Climate Change Opportunity report has been released by EU Commission and two key targets are set for 2020 [7]:

- At least 20 % reduction in greenhouse gases (GHG) by 2020
- Achieving 20% renewable energy share in energy consumption of EU by 2020

The Renewable Energy Directive is published in 23 April 2009. This directive has set national binding targets for EU countries in order to accomplish the 20% renewable energy target for EU and 10 % target for the renewable energy usage in the transport. [8] As a result, each EU country has been determined their national action plans. In order to achieve the 20 % target, each member state determine their own targets ranging from 10% in Malta to 49% in Sweeden. According to the latest release by Eurostat, renewable share of the EU in energy consumption has reached 17 % in 2016

[2]. Moreover, eleven of EU member states has already achieved their 2020 targets. Renewable shares of EU members are shown in Figure 1.3.

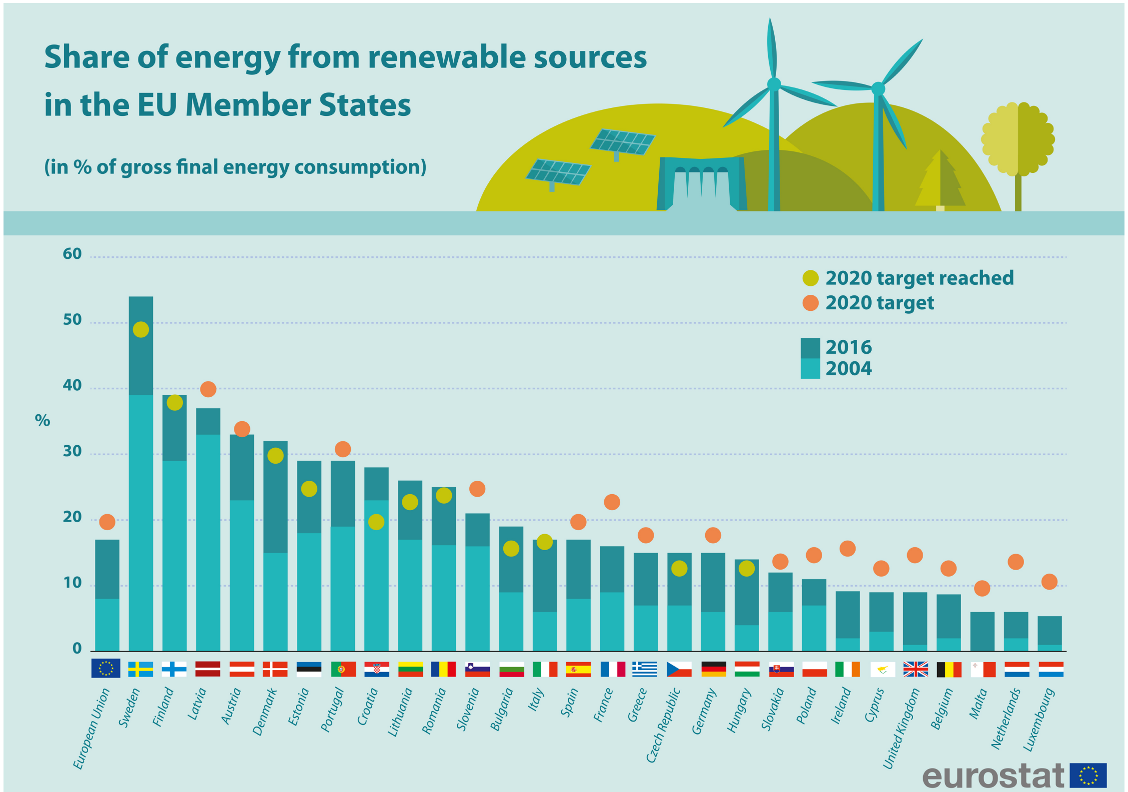


Figure 1.3: Renewable Targets of EU Member States[2]

1.1.2 Wind Energy Status

Wind power has the highest share in the renewable energy except for hydropower. The wind power capacity at the end of 2016 has reached 467 GW worldwide. The wind power capacity of the leading countries are given in the Figure 1.4. China and USA have also the highest installed capacities in the wind power. Moreover, it should also be noted that the share of the wind power in the total installed capacity is more important that total wind power capacity The energy production from wind energy is shown in the Figure 1.5. Even though China has the highest wind power capacity, USA generates more energy from wind than any other country.

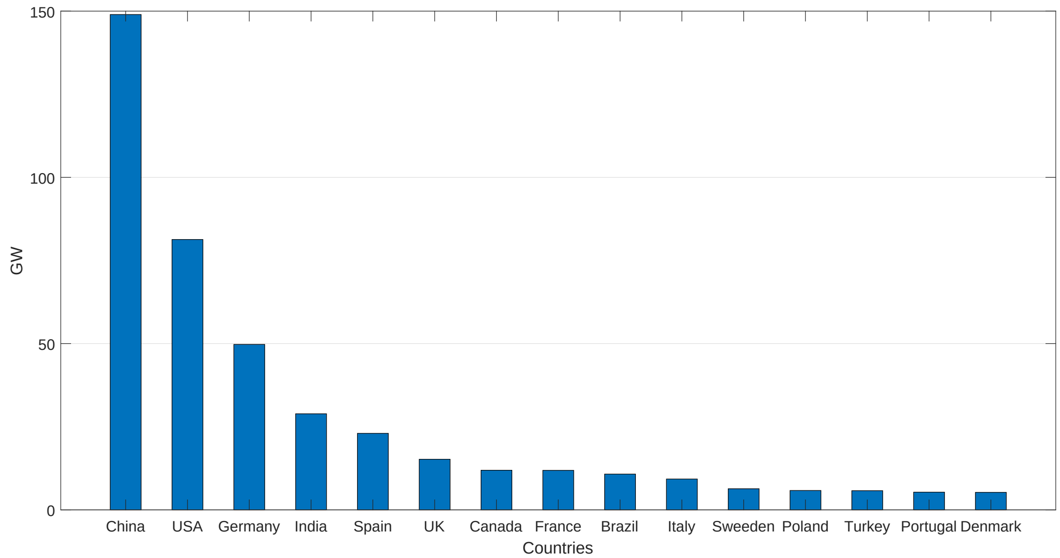


Figure 1.4: Wind Power Capacity of Leading Countries in 2016[1]

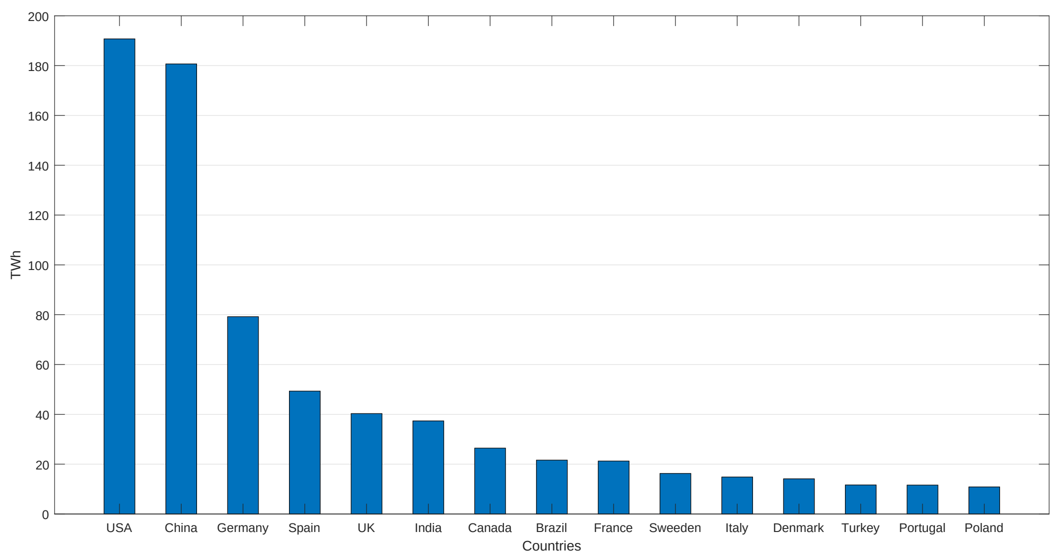


Figure 1.5: Wind Power Production of Leading Countries in 2016[1]

1.2 Global Renewable Energy Future

The share of renewable energy is increasing each passing day. Today, reports arguing the possibility of even 100% renewable energy region by region is published[9]. The renewable energy reports estimate the share of renewable energy in the total energy consumption for 2030 and 2050. Figure 1.6 shows the EU renewable energy share for 2030. Moreover, the report published by IRENA (International Renewable Energy

Agency) estimates the share of renewable energy in EU as 24% by 2030 which is below proposed target of 27%[4].

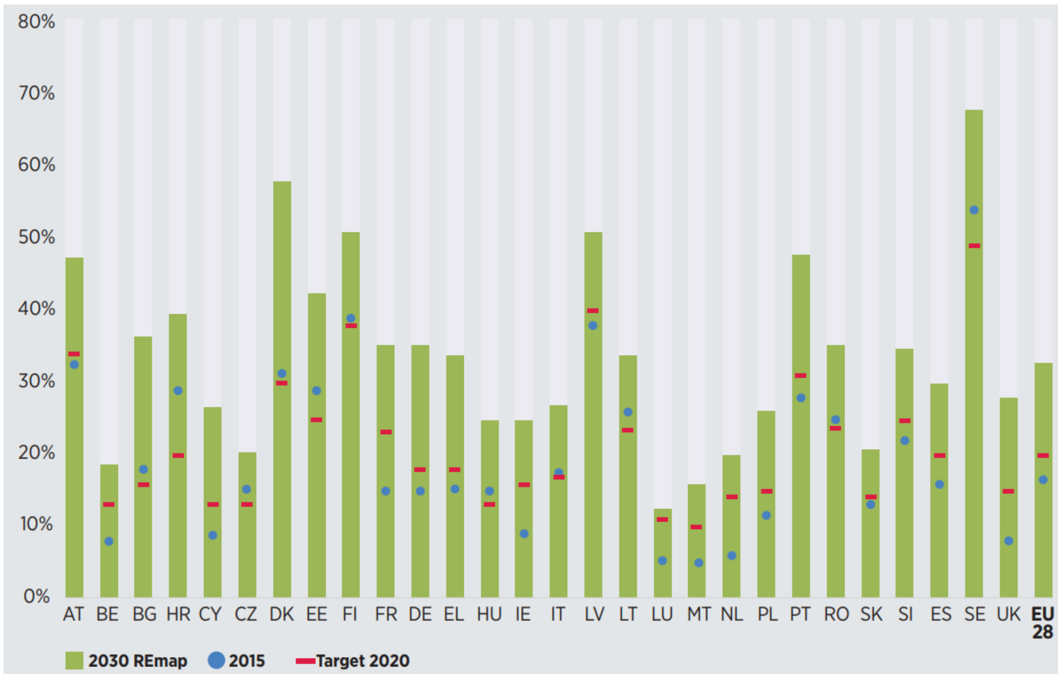


Figure 1.6: Renewable energy share in total energy consumption by EU for 2015, 2020 targets and 2030 potential according to REmap [3]

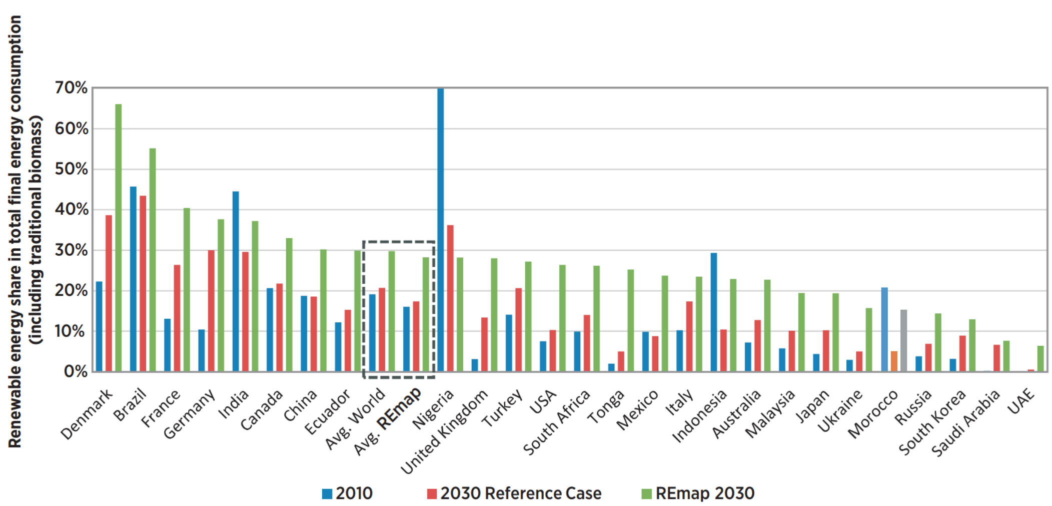


Figure 1.7: Renewable energy shares for 2010, 2030 Reference Case and 2030REmap [4]

Renewable shares of REmap countries in 2010, 2030 reference case and 2030REmap and the world average is also shown in Figure 1.7. The only country whose renewable energy decreases in the 2030 is Nigeria. The reason is the main source of energy in Nigeria is biogas for the time being. However, the renewable share is expected to decrease dramatically as the industry switches to natural gas.

1.3 Renewable Energy Problems

It is an undeniable fact that renewable energy systems are advantageous in terms of global warming and carbon dioxide emission. Nonetheless, they also have disadvantages to the system operators due to intermittent energy generation. With the large penetration of intermittent sources, electric grid will face with transmission system issues as overloaded transmission lines, changes on the protection and control in the distribution system, greater level of power-factor control and low voltage ride-through (LVRT) requirements [10].

Another challenge of renewable energy systems is the power system frequency stability. Since the frequency of the power system depends on the balance between generation and consumotion, grid operators are responsible for adjusting the generation in order to maintain a constant frequency. However, the renewable energy generation is strictly dependent on the renewable source i.e. solar radiation or wind speed. Therefore, renewable systems makes the system operation harder due to their intermittent and uncertain power generation profiles. Moreover, as the renewable systems with power electronics interface increase in the electricity grid, the grid equivalent inertia decreases. In [11], the reduced grid inertia due to the high DFIG wind turbine penetration is emphasized. Moreover, the results of the reduced grid inertia following a disturbance is listed as:

- increased effective aggregated angular acceleration of synchronous machines which require high restoring forces
- high rate of change of frequency and hence, decreased frequency nadir

It should be noted that this problem is not specific to DFIG wind turbines but renewable energy systems which are connected to grid with power electronics. Conventional synchronous generators rotates with synchronous speed which is proportional to grid frequency. If the grid frequency decreases, then the synchronous speed also decreases. In this case, the generator active power is increased inherently due to kinetic energy extraction from the generator inertia. The increase in active power provides action time for primary controllers and crucial for frequency stability. Type-1 and Type-2 wind turbines are directly connected to grid. Hence, the frequency deviations affects the active power output of such wind turbines[12]. Nonetheless, active power output of renewable energy systems with power electronics such as Type-3 and 4 wind turbines and photovoltaic systems is not affected from the grid frequency deviations. Therefore, these system have no contribution to the grid inertia whether the system includes inertia or not. Hence, the aggravated grid inertia is reduced with the penetration of renewable energy sources. Another reason for the decrease in the grid inertia is the de-commitment or dispatch of the conventional sources due to economic concerns. Since the renewable energy has the lowest cost for energy production, it preferred instead of conventional generators. As a result, conventional generators are dispatched to a lower generation profile or taken-off from operation.

1.4 Thesis Motivation

The frequency of the electric grid depends on the balance between generation and consumption. Grid operators are responsible for maintaining this balance so that frequency of the grid is maintained between allowed dead-band. In order to achieve this purpose, power generation is adjusted according to the consumption value. However, the balance between supply and demand might be disturbed with unintentional generator trip or instant load connections. Grid frequency decreases such instants until the generation is increased to arrest the frequency. Inertia of the electric grid provides additional power from the stored kinetic energy and avoid the system frequency from decreasing down very fast. That is called as inertial support and it is very important for power system frequency stability.

Although renewable energy systems are beneficial for environmental concerns and lower energy cost, higher renewable penetration also brings operational challenges for system operators. One of the most important problem that comes with renewable energy is the power system frequency stability. With the high renewable penetration, grid aggravated inertia decreases. As a result, grid frequency deviates steeper for disturbances. To avoid steeper frequency declines in the grid, all generation technologies should provide inertial support for the frequency disturbances.

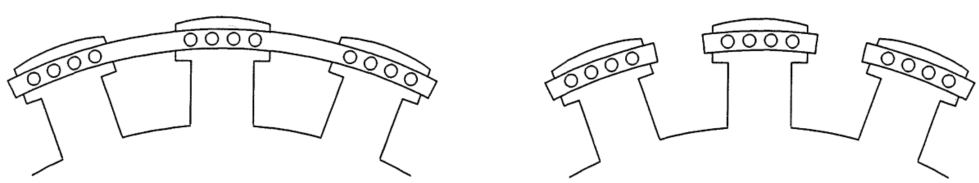
CHAPTER 2

POWER SYSTEM FREQUENCY STABILITY

2.1 Frequency in a Power System

2.1.1 Synchronous Generator and Synchronous Speed

Synchronous machines produce torque only in synchronous speed. This is why they are equipped with damper windings which are basically induction machine windings. If the frequency of grid changes, damper windings create a torque which creates a force to synchronize the speed to the grid frequency. Two type of damper windings are given in Figure 2.1.



(a) continuous damper (b) non-continuous damper

Figure 2.1: Damper windings in a synchronous generator [5]

Due to the damper windings in the rotor, the synchronous machines always operate in synchronous speed. Relation between grid frequency and the synchronous speed is given in 2.3

$$n_s = \frac{120f}{p_f}[5] \tag{2.1}$$

$$n_s = \frac{60}{2\pi}\omega_{syn} \tag{2.2}$$

$$\omega_{syn} = \frac{4\pi f}{p_f} \tag{2.3}$$

where n_s is the synchronous speed in rpm, f is the grid frequency in Hz, p_f is the number of poles of the corresponding generator and ω_{syn} is the synchronous angular speed in rad/s.

2.1.2 Swing Equation

Speed in synchronous machines changes according to the net torque acting on the rotor. Therefore, the speed is maintained constant unless there is no difference between mechanical and electromechanical torque. The equation of motion is given in Eq.2.4 where J is aggravated moment of inertia of the generator and the turbine in kgm^2,T_m and T_e are mechanical and electromechanical torques in Nm.

$$J\frac{d\omega_m}{dt} = T_m - T_e = T_a \tag{2.4}$$

In power system network, the power ratings of the generators and corresponding moment of inertia values varies. Hence, it is more convenient to use inertia constant, H whose unit is seconds and varies between 2 and 9. Inertia constant is defined as the ratio of kinetic energy stored in the inertia to the power rating of the generator as in Eq.2.5 where ω_{0m} denotes the rated angular velocity of generator in rad/s and S_{base} is the rated apparent power in VA.

$$H = \frac{\frac{1}{2}J\omega_{0m}^2}{S_{base}} \tag{2.5}$$

Substituting Eq.2.5 into Eq.2.4 and replacing units to per-unit quantities yield the relation of frequency with power and inertia constant as in Eq.2.10

$$J = \frac{2H}{\omega_{0m}^2}S_{base} \tag{2.6}$$

$$\frac{2H}{\omega_{0m}^2}S_{base}\frac{d\omega_m}{dt} = T_m - T_e \tag{2.7}$$

$$\frac{2H}{\omega_{0m}^2} S_{base}\omega_m \frac{d\omega_m}{dt} = P_m - P_e \tag{2.8}$$

$$2H \frac{\omega_m}{\omega_{0m}} \frac{d(\omega_m/\omega_{0m})}{dt} = \frac{P_m - P_e}{S_{base}} \tag{2.9}$$

$$2H\overline{\omega_m}\frac{d\overline{\omega_m}}{dt} = \overline{P_m} - \overline{P_e} \tag{2.10}$$

2.1.3 Frequency in Power Systems

The frequency in a power system changes according to the swing equation. The equation basically investigates the relation between mechanical and electromechanical powers and the rate of change of angular speed of a generator. Therefore, the speed of an generator remains constant if the mechanical and electromechanical powers are equal.

The electricity grid can also be thought as a single generator whose inertia constant is aggravated from each generator in the network. In this case, average frequency in the network can be found as in Equation 2.11.

$$2H_{sys}\overline{f_{sys}}\frac{d\overline{f_{sys}}}{dt} = \overline{P_m} - \overline{P_e} \tag{2.11}$$

In the Equation 2.11, P_m is the aggravated mechanical input of the generators meanwhile P_e is the aggravated electromechanical output. In other words, the system frequency depends on the balance between generation and consumption. Note that generation means the input mechanical power of the generators.

The behaviour of the frequency in electric grid is given in Figure 2.2. As it can be seen from the water level in a container analogy, the frequency of the system is dependent on the in-flow and the out-flow. Therefore, in the electricity grid, frequency increases as the aggravated input power is higher than the aggravated output power. Note that, the direction of the frequency is dictated by this balance. Having a constant 49.8Hz frequency does not mean that consumption is higher than generation.

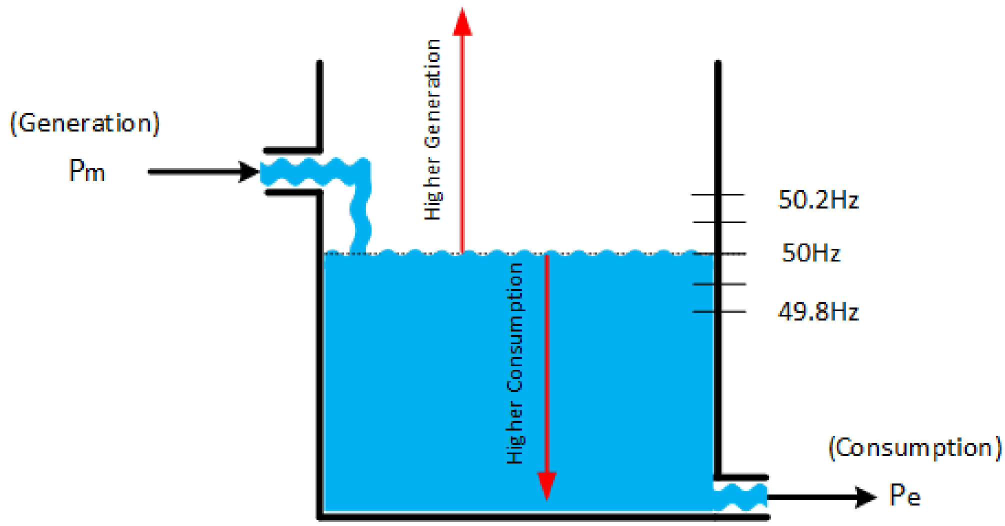


Figure 2.2: Frequency behaviour in electric grid with the water level in a container analogy [6]

Having a constant frequency is one of the most important responsibilities of a system operator. In order to have a constant frequency, supply is being adjusted according to the demand continuously. By doing so, the system frequency varies between a band-gap. The variation depends on the disturbances which are generally a sudden generation outage or instant load connection. The size of the disturbance determines the severity of the frequency change and there are three main mechanisms to arrest the frequency changes in the system.

2.1.3.1 Primary Frequency Controllers

CHAPTER 3

WIND TURBINE MODELLING

3.1 VARIABLE SPEED PMSG WIND TURBINES

The share of variable speed PMSG wind turbines is increasing worldwide due to the high efficiency and torque density. This type of wind turbines are equipped with full-scale power electronics which enable the turbine to have wide speed range. Even though the permanent magnet price fluctuates with time, the reliability and high efficiency of this type of turbine increase its share in the market.

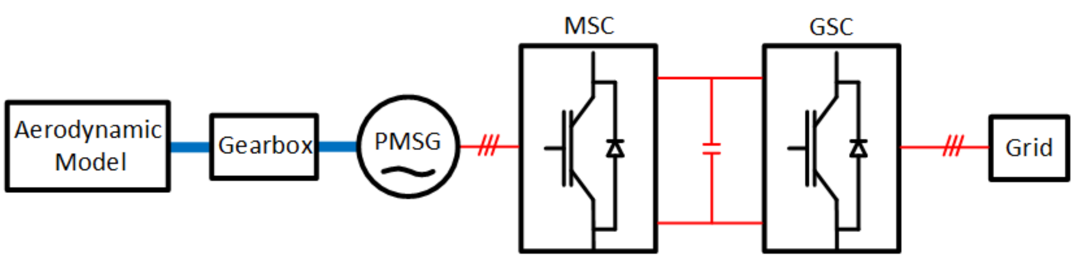


Figure 3.1: Variable Speed Geared Wind Turbine Model

Figure 3.1 shows the modelling of variable speed wind turbine. The aerodynamic sub-model includes turbine structure that captures power from the wind. The gearbox establishes the connection between wind turbine and PMSG. In this type of wind turbines, PMSG is not directly connected to grid so that the turbine speed is independent from the grid frequency. Therefore, back-to-back converter is used between generator and the electrical grid. The converter which is connected to PMSG is called Machine Side Converter (MSC) meanwhile the one connected to grid is called Grid Side Converter(GSC).

3.1.1 Aerodynamic Model

Aerodynamic model is the sub-model that captures power from the wind. The output of this block is the aerodynamic torque that rotates the turbine. However, the wind speed is not the only input. Turbine speed and pitch angle are also the inputs of the system since they affect the mechanical power that is captured from the wind.

The aerodynamic power of wind is given in Equation 3.1 where ρ_{air} is air density in kg/cm^3, R is the blade radius in m abd v_{WIND} is the wind speed in m/s. Note that this is the available power of the air that is striking the turbine swept area and it is not possible to extract that amount of energy. Otherwise, the air would be standstill behind the wind turbine [13].

$$P_{WIND} = 0.5\rho_{air}\pi R^2 v_{WIND}^3 \tag{3.1}$$

The wind turbine captures a fraction of the available wind power that is denominated as power coefficient C_p. Therefore, turbine power captured from wind can be found with the Equation 3.2.

$$P_{TUR} = C_P P_{WIND} \tag{3.2}$$

Power coefficient determines the amount of power and it is a non-linear function of the tip speed ratio, λ and pitch angle, β. Tip speed ratio is a parameter proportional with turbine speed. It can be defined as the ratio of the speed in the turbine tip to the wind speed as in the Equation 3.3. Power coefficient for a specific tip speed ratio and pitch angle can be found with the Equation 3.4 and 3.5 where c_1 is 0.5176, c_2 is 116, c_3 is 0.4, c_4 is 5, c_5 is 21 and c_6 is 0.0068 [14].

$$\lambda = \frac{\omega_{tur} R}{v_{WIND}} \tag{3.3}$$

$$C_p(\lambda, \beta) = c_1(c_2/\lambda_i - c_3\beta - c_4)e^{-c_5/\lambda i} + c_6\lambda \tag{3.4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.5}$$

Variation of power coefficient C_p is given in Figure 3.2. For the zero pitch angle, power coefficient has the maximum value of 0.48 for the tip speed ratio of 8.1. In order to ensure that the maximum of wind power is extracted, wind turbine should rotate a speed that gives the optimum tip speed ratio.

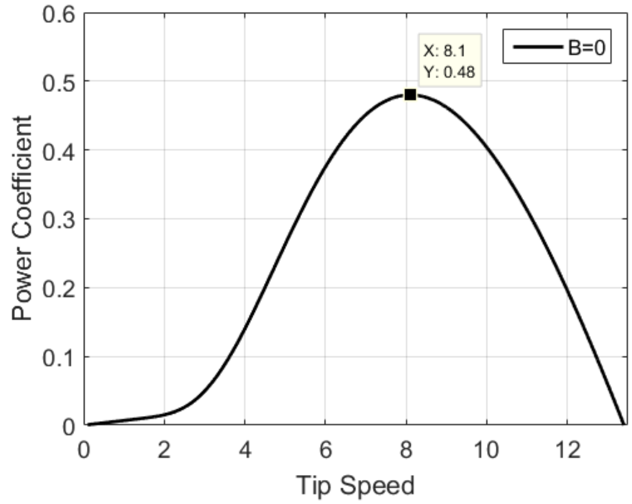


Figure 3.2: Power Coefficient Variation with Tip Speed Ratio under Zero Pitch Angle

3.1.2 Gearbox

Variable speed PMSG wind turbines have a gearbox between turbine and generator except for direct-drive wind turbines. The gearbox increases angular speed and decreases the torque in the generator side.By decreasing the rated torque, generator size and cost can be reduced since the generator size is almost proportional to rated torque due to constant shear stress [**?**].

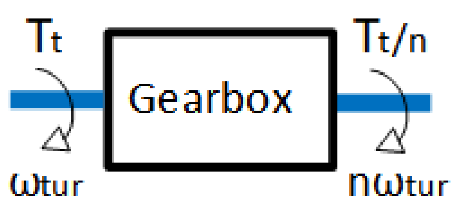


Figure 3.3: Gearbox Modelling

3.1.3 Permanent Magnet Synchronous Generator

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APPENDIX A

EK A

A.1 Örnek Kısım

Kısım içine yazılacaklar...