INERTIAL SUPPORT IMPLEMENTATION IN VARIABLE SPEED PMSG WIND
TURBINES

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ABSTRACT

INERTIAL SUPPORT IMPLEMENTATION IN VARIABLE SPEED PMSG WIND TURBINES

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LIST OF ABBREVIATIONS

AGC   Automatic Generation Control

DFIG   Doubly Fed Induction Generator

PMSG   Permanent Magnet Synchronous Generator

MSC   Machine Side Converter or Controller

GSC   Grid Side Converter or Controller

LSC   Line Side Converter or Controller

AC   Alternating Current

DC   Direct Current

MOSFET   Metal Oxide Semiconductor Field Effect Transistor

IGBT   Insulated Gate Bipolar Transistor

PI   Proportional-integral

LVRT   Low Voltage Ride-Through

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.
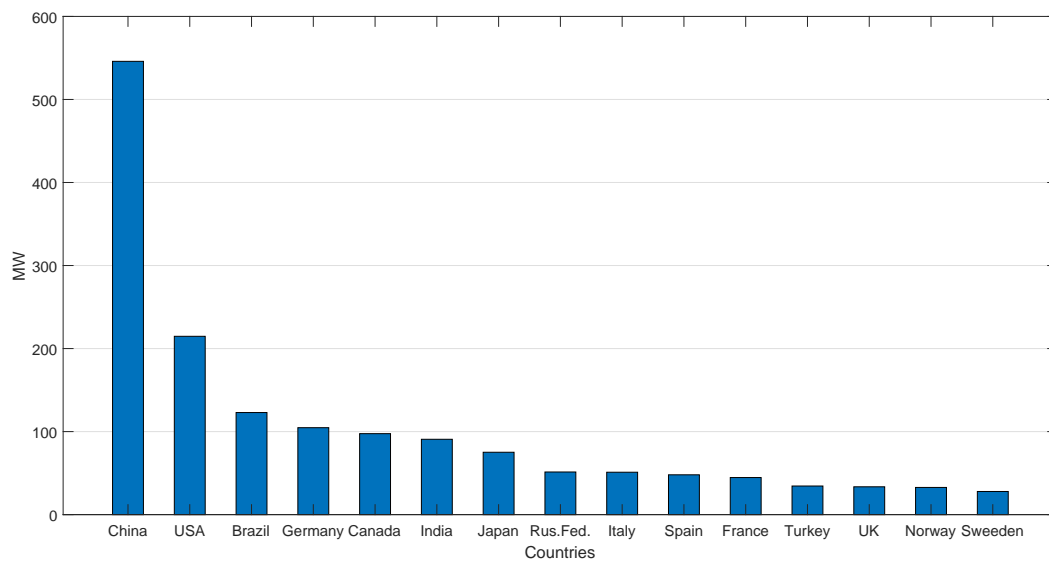

Figure 1.1: Installed Renewable Energy Capacity of Leading Countries in 2016[1]

Figure 1.2 shows the energy production from 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
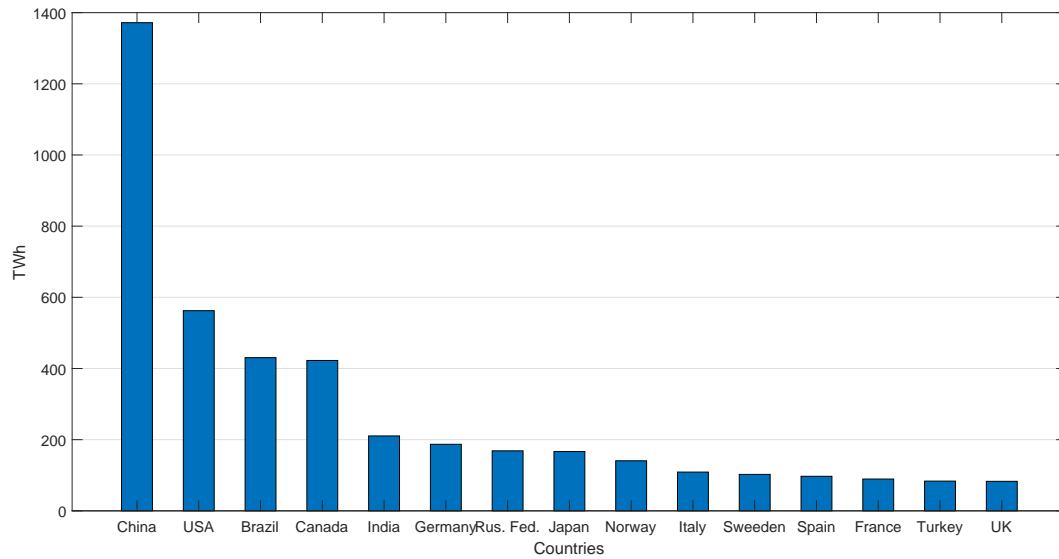
Figure 1.2: Renewable Energy Production of Leading Countries in 2016 [1]

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.

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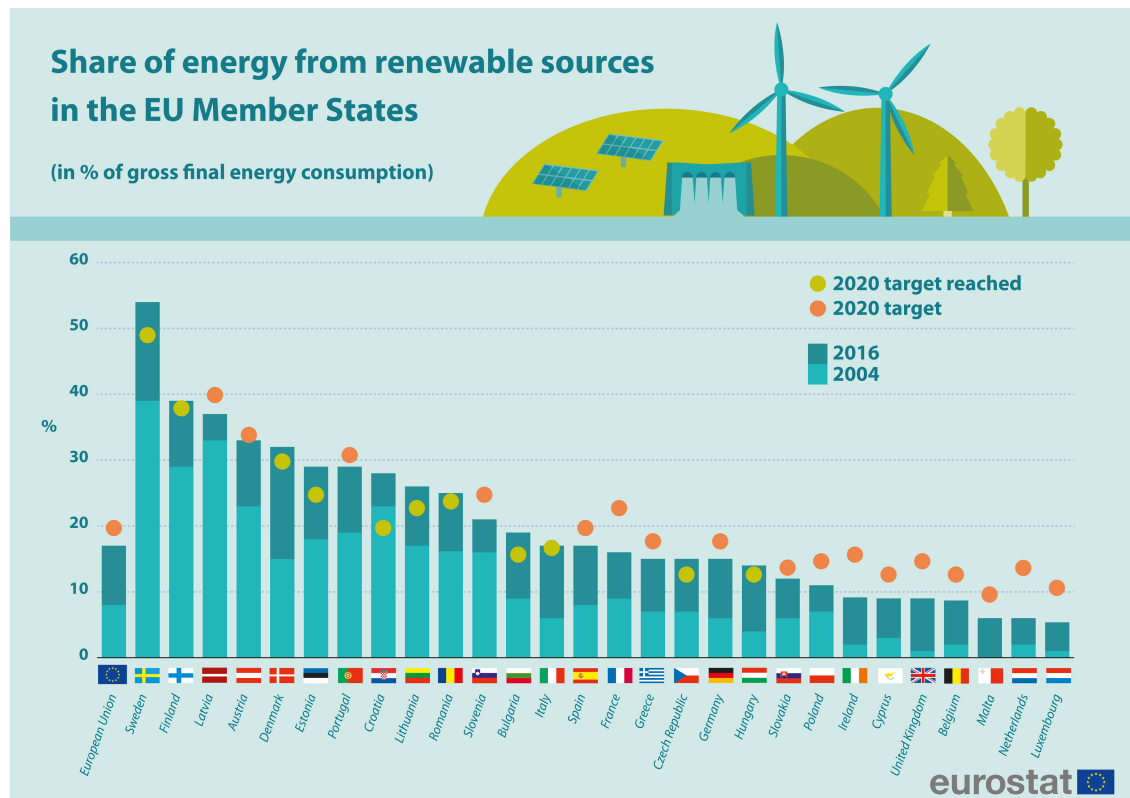
Figure 1.3: Renewable Targets of EU Member States[2]

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.
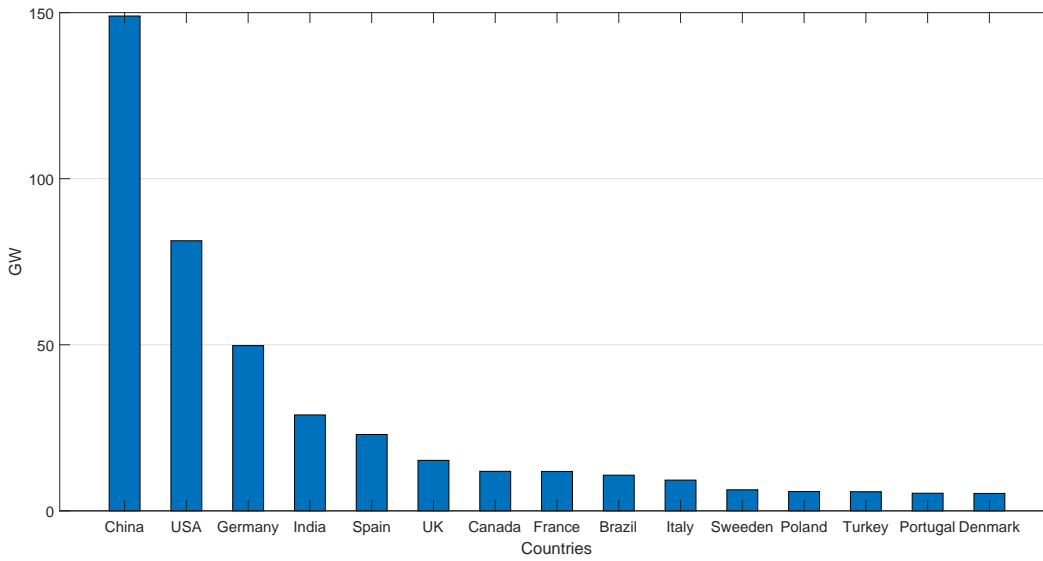
Figure 1.4: Wind Power Capacity of Leading Countries in 2016[1]
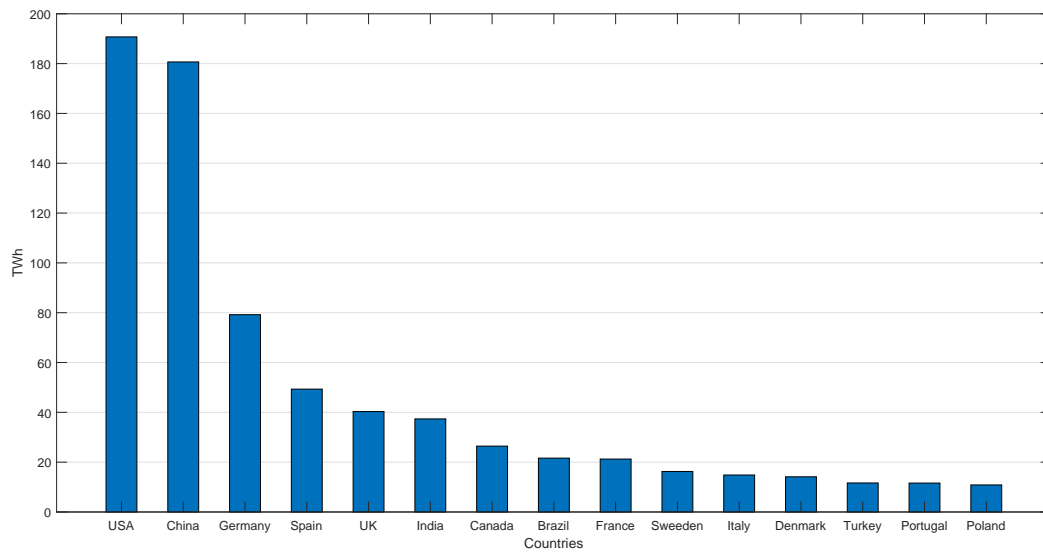
Figure 1.5: Wind Power Production of Leading Countries in 2016[1]

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].
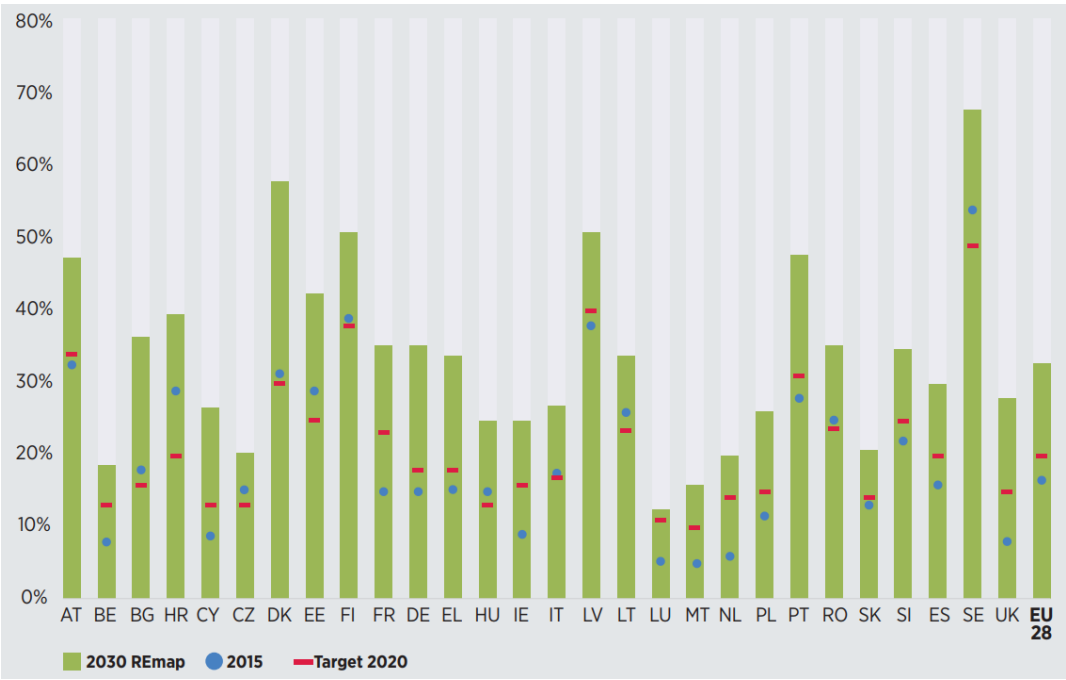
Figure 1.6: Renewable energy share in total energy consumption by EU for 2015, 2020 targets and 2030 potential according to REmap [3]
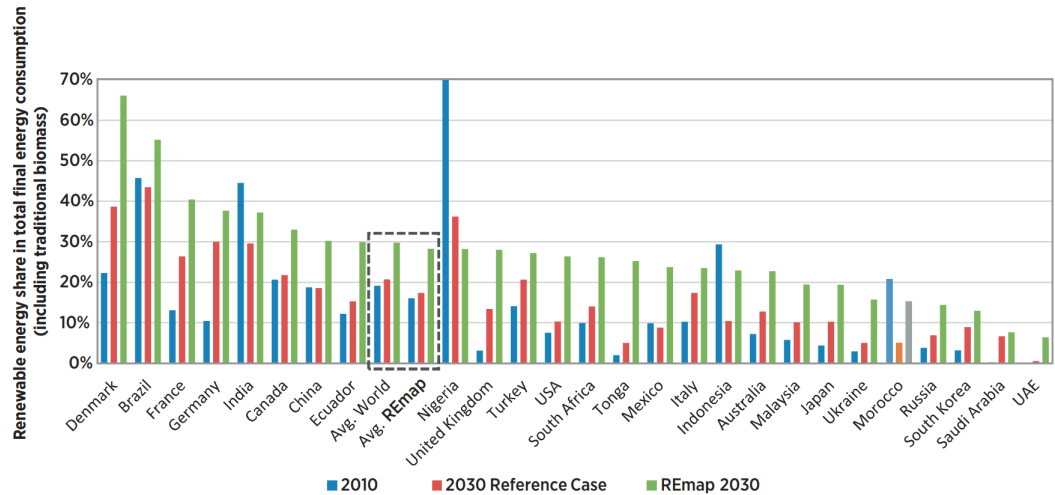
Figure 1.7: Renewable energy shares for 2010, 2030 Reference Case and 2030REmap [4]

Renewable shares of REmap countries in 2010, 2030 reference case and 2030REmap

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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 renew-

able 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   Literature Review

Studies regarding inertial support date back to earl 2000s. In the study [13], the effect of the increasing wind energy penetration has been investigated. The study concludes that increasing share of wind energy increases the primary reserve requirement for the successful grid operation. The increased frequency deviations, especially in light load conditions (high wind generation with low consumption scenario) can be mitigated in the system as long as the wind generation provides inertia support. Study in [14] states that DFIG wind turbines are de-coupled from power system resulting in no contribution to system inertia. A supplementary loop is proposed for reinstating the machine inertia. Moreover, in [15], performance of the supplementary control loop is evaluated with the comparison of the inertial support of a fixed-speed wind turbine. The proposed control loop has been validated in [16] and compared with the droop control in [17].

1.5 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 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
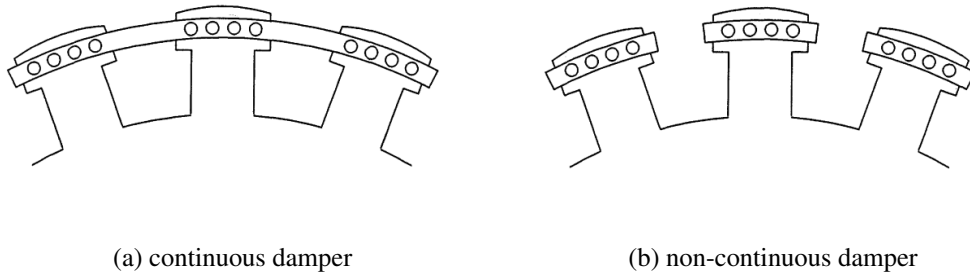
Figure 2.1: Damper windings in a synchronous generator [5]

The synchronous machines keep their operation in the synchronous speed thanks to the damper windings in the rotor. Relation between grid frequency and the synchronous speed is given in Equation 2.1 in terms of rpm. [5]. This equation can be better observed in Equation 2.3

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

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

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

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 generator and ω_{syn} is the synchronous angular speed in rad/s.

2.2 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 [5]. 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

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

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

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

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

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

2.3 Frequency in Power Systems

The frequency in a power system is related to the speed of the synchronous generators and changes according to the swing equation. The frequency of the each generator is not the same in the network since each generator does not have the same speed. There are always fluctuations in the power system. However, the network can be assumed as a single generating unit by neglecting this assumption. The swing 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.

If the electricity grid is considered as a single generator, the inertia of the equivalent generator is aggravated from each generator in the network. In this case, average frequency in the network can be found as in Eq. 2.11.

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

where P_m is the aggravated mechanical input power of the generators meanwhile P_e is the aggravated electromechanical output power. 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
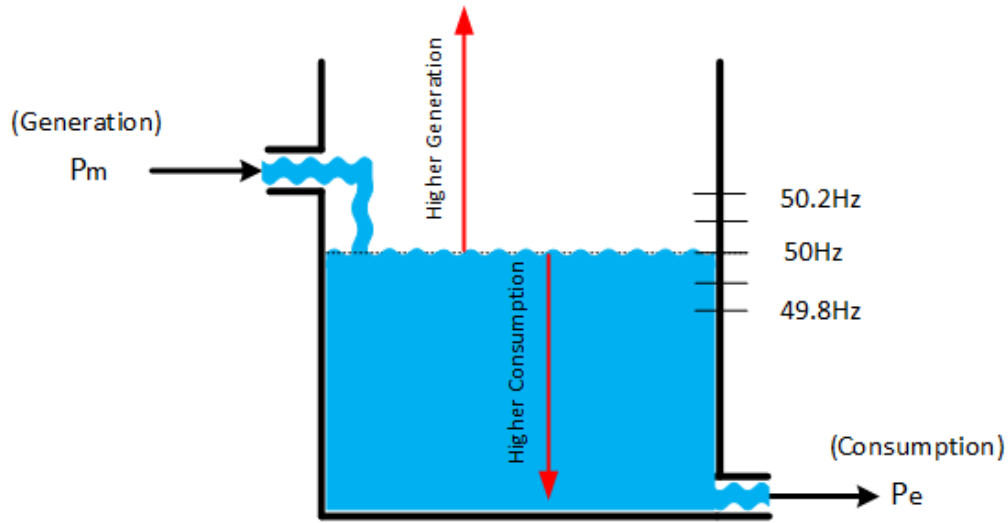

Figure 2.2: Frequency behaviour in electric grid with the water level in a container analogy [6]

of the frequency in electric grid is depicted in Fig. 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. If the frequency is constant, then the input mechanical power is equal to output power.

2.3.1 Primary Frequency Control

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.

Following generator outage or sudden load connection event, frequency start decreasing. The slope of the frequency is dependent on the severity of the event by means of power and the available inertia of the power system. Such frequency disturbance requires increased input power. However, the increase in the input mechanical power should be activated very fast and should be automated. This responsibility is assigned to generating units with primary control. The active power generation of these units is increased or decreased by the governor depending on the network frequency direction. Note that each generator in the power system does not necessarily perform primary control function. In this case, their active power generation is independent from the network frequency. Hence, the decrease in the frequency is arrested by the primary frequency control. The primary controllers act during a few seconds following a disturbance. They keep their operation up to 30 minutes.

2.3.2 Secondary and Tertiary Control

The frequency is recovered back to nominal value with the Secondary Frequency Control action. This controller might be a single or multiple centres that monitor the frequency and adjust the generation accordingly. They are also called as Automatic Generation Control (AGC) systems and their action takes a few minutes. The final frequency control mechanism is the Tertiary Frequency Control. If the frequency is not recovered back to nominal value with the secondary controllers, tertiary frequency controllers manually activates the load shedding which is an undesired situation by the network operator. However, it is an emergency case which might result in blackout and requires immediate action.

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.
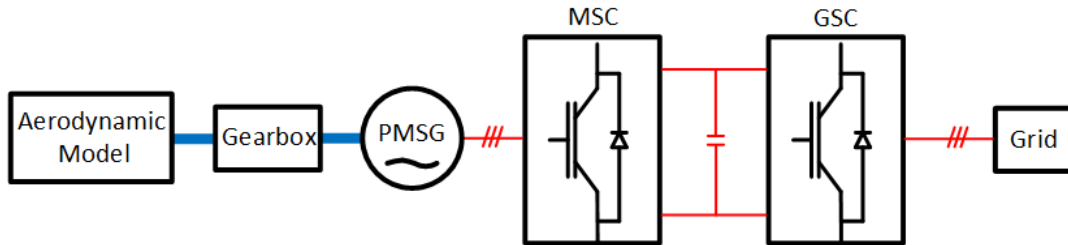
Figure 3.1: Variable Speed Geared Wind Turbine Model

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 [18].

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

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 [19].

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

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

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

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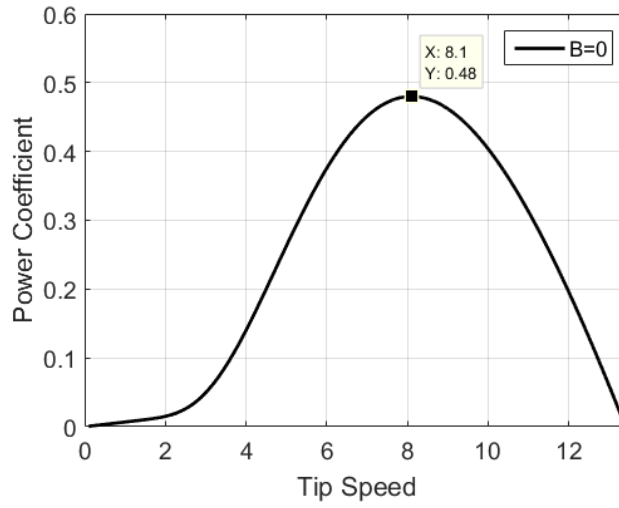
Figure 3.2: Power Coefficient Variation with Tip Speed Ratio under Zero Pitch Angle

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 [20]. Moreover, turbine speed is increased to the allowable speed range of the generator which is generally much higher than that of wind turbines. Otherwise, generator should have high pole numbers.
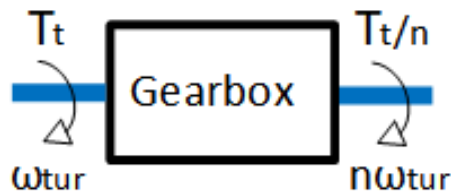

Figure 3.3: Gearbox Modelling

3.1.3 Permanent Magnet Synchronous Generator

PMSGs are generally preferred over electrically excited synchronous generators due to high efficiency. Absence of electrical excitation on the rotor decreases losses. Besides, slip ring is not needed in the generator which also decrease the maintenance. Dynamical equations of the salient pole PMSG are projected on a reference frame which rotates synchronously with magnet flux and given in Equations 3.6 and 3.7 where R_1 is stator resistance in Ω, L_{sd} and L_{sq} are d and q axis inductances in H, i_{ad} and i_{aq} are d and q axis currents in A, ω is the electrical angular frequency in rad/s ψ_f is magnet flux linkage in Vs [18].

$$v_{1d} = R_1 i_{ad} + L_{sd}\frac{di_{ad}}{dt} - L_{sq}\omega i_{sq} \tag{3.6}$$

$$v_{1q} = R_1 i_{aq} + L_{sq}\frac{di_{aq}}{dt} + L_{sd}\omega i_{sd} + \omega\psi_f \tag{3.7}$$

Another important PMSG parameter is the power in dq frame. The power expression is given in Equation 3.8. The electromechanical torque can be found by the relation between power and angular speed. The torque expression is also given in Equation 3.9 where p is the number of pole pair.

$$P_{elm} = \frac{3}{2}\omega i_{aq}(\psi_f + i_{ad}(L_{sq} - L_{sd})) \tag{3.8}$$

$$T_e = \frac{P_{elm}}{w_m} = \frac{P_{elm}}{w/p} = \frac{3}{2}p i_{aq}(\psi_f + i_{ad}(L_{sq} - L_{sd})) \tag{3.9}$$

Given equations are defined for salient pole machines. If the clyndrical rotor machine is used, the torque equation reduces to the Equation 3.10.

$$T_e = \frac{3}{2}p i_{aq}\psi_f \tag{3.10}$$

3.1.4 Machine Side Converter

Variable speed wind turbines are equipped with the Back-to-Back converters in order to decouple grid frequency and the turbine speed. This gives wind turbine degree of freedom for the rotational speed. In this way, turbine is able to capture the maximum

available power in wind. Machine Side Converter (MSC) i.e. Generator Side Converter is the converter that is connected between generator and DC-bus. The three phase generator output AC voltage is converted to DC voltage. Conversion from AC to DC can be achieved by three-arm full bridge converters. This converter can be equipped with uncontrolled, semi-controlled and fully-controlled switches. Fully-controlled switches such as MOSFET,IGBT are commonly used in the industry and gives two control parameters to the user.

Voltages and currents are generally transformed into synchronously rotating reference frame or also called dq frame. Since the frame is rotating in synchronous speed, three-phase phasors transform into DC quantities. Therefore its control becomes easier [21]. Proportional-integral (PI) controllers are associated with the dq control structure due to their satisfactory behaviour interaction to DC variables [22]. Hence, the control in the back-to-back converter is achieved with PI controllers in the dq frame.
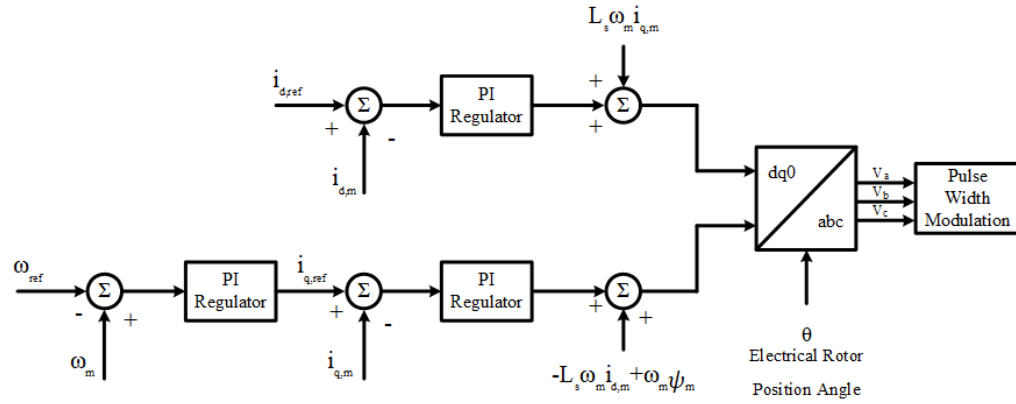

Figure 3.4: Machine Side Control Diagram

The control diagram of the MSC is depicted in Figure 3.4 according to the study in [23]. In dq frame, it is possible to control two parameters. One of these parameters is the d-axis current. It can be set zero in order to decrease the stator copper losses. The other parameter is the q-axis current that is proportional to the electromagnetic torque as it can be observed in the Equation 3.10. However, q-axis current or torque is controlled in order to regulate the turbine speed. Therefore, turbine speed is adjusted such that the turbine will capture maximum available power in the wind.

3.1.5 Grid Side Converter

Grid Side Converter (GSC) or Line Side Converter (LSC) is the converter that is connected between DC-link capacitance and grid. GSC works as an inverter that injects current synchronous with grid voltage. Currents and voltages are transformed into synchronously rotating frame that is aligned with the grid voltage. Therefore, d-axis current determines the amount of current which is in phase with the grid voltage meanwhile q-axis current determines amount of current that is out of phase with the grid voltage. In other words, injecting d-axis current injects active power to grid meantime q-axis current injects reactive power to grid.

The responsibility of the GSC is regulating DC voltage and the reactive power injected to grid. The control diagram of the GSC is given in Figure 3.5. As seen from the figure, DC-bus voltage is regulated by controlling the d axis current. If the DC-bus voltage increases above the reference value, d-axis current reference is increased. As a result, active power increases. Increased active power also decreases the DC-bus voltage level. Reference value of the q-axis current is set to zero in normal operation, consequently unity power factor. For Low Voltage Ride-Through studies, q-axis current is determined according to the reactive power value requirement. [24]
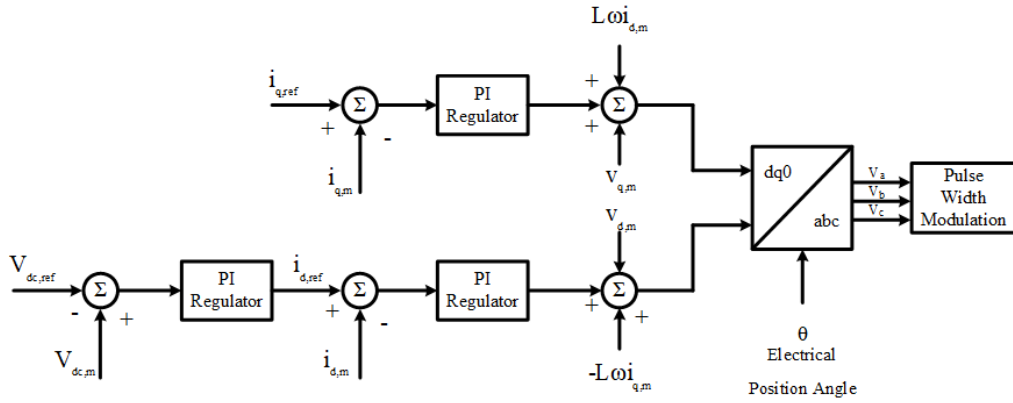

Figure 3.5: Grid Side Control Diagram

GSC is connected to grid through an filter. Therefore, the output voltage of the converter is not equal to the that of grid. The relation between converter voltage, grid voltage and current is derived through Equations 3.11 to 3.17 where v_c is the converter voltage, v_g is the grid voltage and i_g is the grid current measured in the grid

side. As it is observed in Equation 3.16 an 3.17, converter side voltage includes same axis grid voltage and a term proportional to cross axis current which is called cross-coupled term. Therefore, the outputs of the inner PI regulators are compensated and forwarded to Pulse Width Modulation after transformation to three-phase voltages.

$$\overline{v_c} = v_{dc} + jv_{qc} \tag{3.11}$$

$$\overline{v_g} = v_{dg} + jv_{qg} \tag{3.12}$$

$$\overline{i_g} = i_{dg} + ji_{qg} \tag{3.13}$$

$$\overline{v_c} = \overline{v_g} + \overline{i_g}j\omega L \tag{3.14}$$

$$v_{dc} + jv_{qc} = v_{dg} + jv_{qg} + j\omega L(i_{dg} + ji_{qg}) \tag{3.15}$$

$$v_{dc} = v_{dg} - \omega Li_{qg} \tag{3.16}$$

$$v_{qc} = v_{qg} + \omega Li_{dg} \tag{3.17}$$

CHAPTER 4

VALIDATION IN TEST CASE

4.1 Örnek Kısım

Kısıma yazılacaklar...

Bölüme referans vermek için A

REFERENCES

[1] International Renewable Energy Agency, *Renewable Energy Statistics 2017*. 2017.

[2] Eurostat, "Renewable energy in the EU-newsrelease," Tech. Rep. January, 2018.

[3] European Commission; and IRENA International Renewable Energy Agency, "Renewable Energy Prospects for the European Union," Tech. Rep. February, 2018.

[4] IRENA, "A Renewable Energy Roadmap," Tech. Rep. June, 2014.

[5] P. Kundur, *Power System Stability and Control*. McGraw-Hill,Inc.

[6] J. Eto, J. Undrill, P. Mackin, R. Daschmans, B. Williams, B. Haney, R. Hunt, J. Ellis, H. Illian, C. Martinez, M. OMalley, K. Coughlin, and K. Hamachi-LaCommare, "Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation," no. December 2010, pp. LBNL–4142E, 2010.

[7] European Commission, "Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions - 20 20 by 2020 - Europe's climate change opportunity," *COM (2008) 30 final*, p. Brussels, 2008.

[8] European Parliament, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009," *Official Journal of the European Union*, vol. 140, no. 16, pp. 16–62, 2009.

[9] REN21, *Renewables Global Futures Report*. 2017.

[10] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power and Energy Magazine*, vol. 7, no. 2, pp. 52–62, 2009.

[11] D. Gautam, L. Goel, R. Ayyanar, V. Vittal, and T. Harbour, "Control strategy to mitigate the impact of reduced inertia due to doubly fed induction generators on large power systems," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 214–224, 2011.

[12] E. Muljadi, V. Gevorgian, and M. Singh, "Understanding Inertial and Frequency Response of Wind Power Plants Preprint," *2012 IEEE Power Electronics and Machines in Wind Applications (PEMWA)*, no. July, pp. 1–8, 2012.

[13] G. Lalor, J. Ritchie, S. Rourke, D. Flynn, and M. O'Malley, "Dynamic frequency control with increasing wind generation," *IEEE Power Engineering Society General Meeting, 2004.*, pp. 1–6, 2004.

[14] J. Ekanayake, "Control of DFIG wind turbines," *Power Engineer*, vol. 17, no. 1, pp. 28–32, 2003.

[15] J. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," *IEEE Transactions on Energy Conversion*, vol. 19, no. 4, pp. 800–802, 2004.

[16] J. Morren, S. de Haan, W. Kling, and J. Ferreira, "Wind Turbines Emulating Inertia and Supporting Primary Frequency Control," *IEEE Transactions on Power Systems*, vol. 21, no. 1, pp. 433–434, 2006.

[17] J. Morren, J. Pierik, and S. W. de Haan, "Inertial response of variable speed wind turbines," *Electric Power Systems Research*, vol. 76, no. 11, pp. 980–987, 2006.

[18] T. Ackermann, *Wind Power in Power Systems Wind Power in Power Systems Edited by*, vol. 8. 2005.

[19] S. Heier, *Grid Integration of Wind Energy*. 3 ed., 1998.

[20] H. Polinder, J. A. Ferreira, B. B. Jensen, A. B. Abrahamsen, K. Atallah, and R. a. McMahon, "Trends in Wind Turbine Generator Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 174–185, 2013.

[21] M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, *Control in Power Electronics—Selected Problems*. New York: Academic, 2002.

[22] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1398–1409, 2006.

[23] M. Chinchilla, S. Arnaltes, and J. C. Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid," *IEEE Transactions on Energy Conversion*, vol. 21, no. 1, pp. 130–135, 2006.

[24] T. Orłowska-Kowalska, F. Blaabjerg, and J. Rodríguez, *Advanced and intelligent control in power electronics and drives*. 2014.

APPENDIX A

EK A

A.1 Örnek Kısım

Kısım içine yazılacaklar...