Chapter 1: Introduction

1.1 Introduction to the Research

We don't need nuclear power, coal or biofuels. We can get 100 percent of our energy from wind, water and solar (WWS) power. All we need is the wind, the water, and the sun. We can get to this WWS world by simply building a lot of new systems for the production, transmission and use of energy. A 100 percent wind, water and solar power system can deliver all of the world's energy needs efficiently (Delucchi, 2011).

This research is on balancing and stabilization of 100% renewable electric power system. The study will contribute to the realisation of implementing 100% renewable electricity targets in countries of the world which currently in the implementation phase. This is in one side to form a 100% renewable energy model and in the other side to control the electrical power system especially in frequency stability. In other words, it can be described as this effort is to find the possibility of forming a 100% renewable energy system and operate it in stabilized manner.

The research includes a step wise approach the modelling of the 100 percent renewable electricity generation target, starting from potential studies of renewable energy sources. Then, it determines the optimum generation mix of different energy sources and capacity estimation for bulk energy storage system. Finally, it addresses the behaviour of power system frequency and determines the mandatory requirement of synchronous generation for frequency stability. As a secondary outcome of the research, some favourable further research areas arising from this research were analysed and the sustainable development benefits of a 100% renewable scenario have been identified and quantified.

This research gives a deep insight into the forming of 100 percent renewable energy model and its frequency stability targets. The transparently conveyed assumptions and calculations will build a robust basis for future opening research areas on similar matters.

This thesis report has been developed with the purpose of designing and proposing renewable energy scenarios and mechanisms through which the goal of achieving

Chapter 5:
Time Scale Study of Energy Model

5.1 Introduction

The frequency of a power system is one indicator of the quality of the electricity supply. The operating limits of the frequencies may be defined as a statutory requirement or may be self imposed by the network operator. It is imperative from a security perspective to maintain frequency deviations within small tolerances of nominal operating frequency in order to avoid customer interruption, additional generator trip events and in extreme cases the risk of cascading system blackout (O'Sullivan, et al., 2014).

This chapter will analyse the power system frequency response with respect to time line corresponding to power system disturbances with the intermittence nature of renewable energy sources. Further, it details current practices and recommendations relating to the management of frequency response of renewable rich power system, minimum inertia required to maintain inertial response, a review on primary frequency control methods and power system oscillations and damping, etc. A comprehensive mathematical modelling of frequency response of a renewable rich power system is carried out in Chapter 06.

5.2 Time Scale Structure

Power system frequency response can be categorized in to three main regions, those are inertial response, primary frequency response and automatic generation control (also called secondary frequency response).

Sometimes the most important classification of dynamic phenomena of power system is their natural time range of response. A typical classification of different power system phenomenon is shown in figure 5.1 as per the description in (Sauer & Pai, 1998).

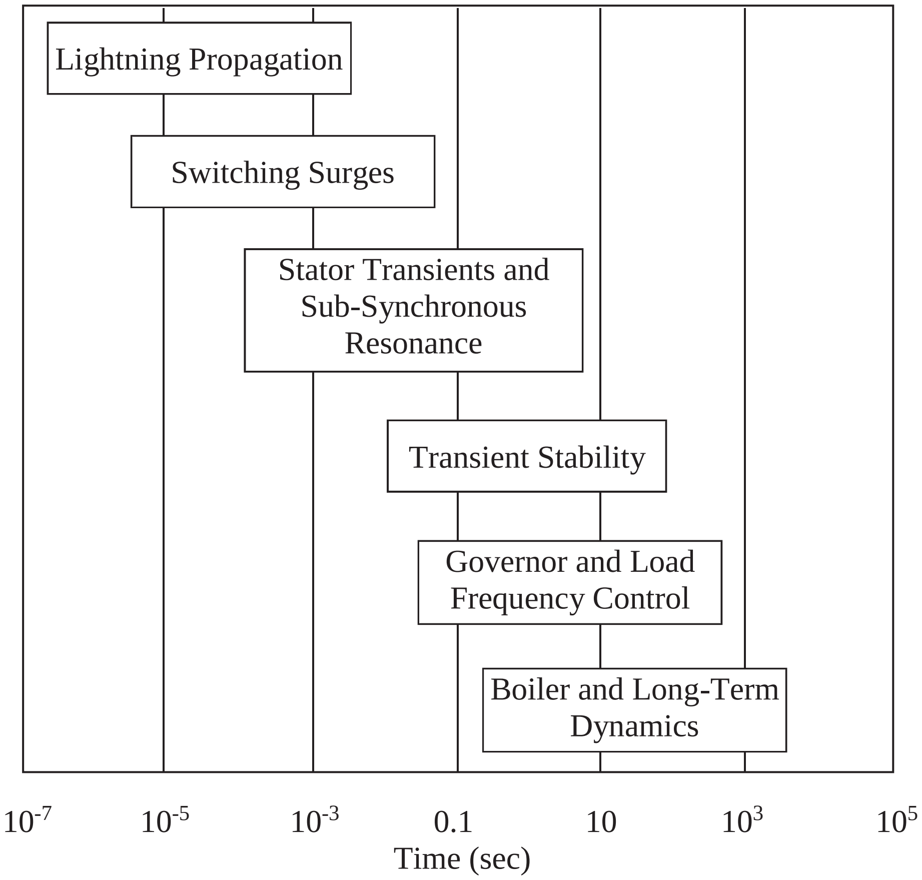

Figure 5.1: Time Ranges of Dynamic Phenomena (Sauer & Pai, 1998)

(NREL, 2013) describes the three distinct regions of power system frequency response in detail. When a disturbance occurs, the frequency of the electric power system deviates from its scheduled level. The frequency must be stabilized and returned to its scheduled level to avoid further reliability issues. Figure 5.2 shows the three distinct regions of frequency response of a power system. The initial rate of change of frequency (initial slope) is determined by the total inertia of the power system. The time range is around 0 to 10 seconds. Then it starts with primary frequency control with the help of droop mechanism of reserved power plants. It can take place up to 30 seconds. Then, it starts secondary control of the power system in minute range of time.

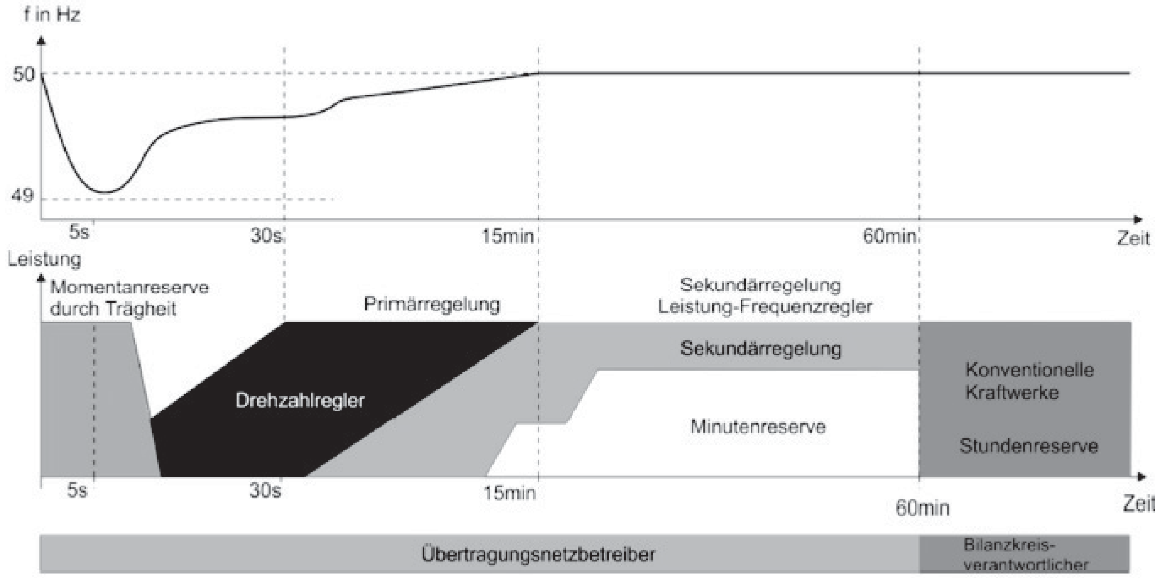

Figure 5.2: Frequency Response Phenomena (EFZN, 2017)

5.2.1 Inertial Response

Inertial response is the immediate response to any power system disturbance that causes a power system frequency deviation, for an example, that may be a loss of large generator or a large loss of load. Inertial response is important because it reduces the rate of change of frequency (RoCoF) after a disturbance, which can lead to avoidance of under frequency load shedding or worse issues, including blackouts (NREL, 2013). Conventional synchronous generators provide inertial response naturally from stored energy in the rotating mass of their turbines.

5.2.2 Role of Wind and Solar in Inertial Response

Nowadays, large scale wind power generations and solar PV systems connect to the main grid via power electronics based converters, which isolate the wind and solar generations from grid frequency and enable advanced control functions. In spite of the availability of a relatively large stored rotational energy resource in wind turbines, the decoupling of the mechanical rotating mass of power electronic based Doubly Fed Induction Generators (DFIG) and Full Converter Wind Turbine Generator (FCWTG) from the synchronous system dynamics impacts the overall inertial response characteristic (Ruttledge & Flynn, 2011).

5.6 Small Signal Stability

This section investigates the impact of a large solar and wind energy penetration on power system small signal oscillation stability. The two hydro power plants (four synchronous generators) are reduced to equivalent synchronous machine in the system. It is approximated to single machine infinite bus power system integrated with a PV and wind power plants.

Natural frequency of a machine is a unique and specific property of this machine and it is not considered a fixed parameter for it. It changes according to many factors, such as the machine connection, whether is it connected to an infinite bus network or forms a single standalone generator supplying local loads or it is connected in parallel with other machines at a power network (Abdel-moamen, Mohamed , & Badr, 2017).

Huge stable power systems tend to reach the stability state after being hit by any type of power impacts. They tend to stay intact and none of their connected generators go out of step. Each generator, just after the impact instant, starts to have a different power angle from its initial value. It swings trying to reach a new stable pole angle (Anderson & Fouad, 1977).

The equation of motion or the swing equation may be written as in equation 5.13 as per the reference (Kundur, 1994).

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_m - P_{max}\sin\delta \qquad \ldots (5.13)$$

Where,

P_m	-	Mechanical power input in per unit
P_{max}	-	Maximum electrical power output in per unit
H	-	Equivalent inertia constant in MWs/MVA
δ	-	Rotor angle in elec. rad
t	-	Time in s
ω_0	-	Rated angular velocity of the rotor in elec. rad/s

When some power system disturbance occurs due to the intermittent nature of wind and solar generations, the reduction of electricity generation from solar and wind power sources has to be taken from synchronous machines of conventional hydro power plants. At the start and after applying the loads to the synchronous generators, each machine (power plant) oscillates according to its natural frequency due to its inertia constant and pole pairs. The rate of change of speed of rotor can be expressed as in equation 5.14, according to (Anderson & Fouad, 1977).

$$\dot{\omega} = \frac{\omega_r}{2H}\ [P_m - \ P_e(t)] \qquad \dots (5.14)$$

From equation 5.13, we have the relationship shown in equation 5.15 between the rotor angle and the accelerating power:

$$\frac{d^2\delta}{dt^2} = \frac{\omega_0}{2H}\ (P_m - P_e) \qquad \dots (5.15)$$

Where,

P_e - Electrical power output in per unit

When the load is increased by ΔP, as a result of which the load angle changes by Δδ, then the accelerating power is ΔP and the swing equation can be linearized around the stabilizing point as follows;

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{\omega_0(P_m - P_e)}{H}\ \frac{d\delta}{dt}$$

$$\left[\frac{d\delta}{dt}\right]^2 = \int \frac{\omega_0(P_m - P_e)}{2H}\ d\delta \qquad \dots (5.16)$$

The typical solution of equation 5.16 can be written as in equation 5.17.

$$\left[\frac{d\delta}{dt}\right]^2 = \left[\frac{\omega_0(P_m - P_e)}{2H}\delta\right] + A \qquad \dots (5.17)$$

Since at t = 0 the system is in steady state and *dδ/dt = 0*. Therefore, by applying the initial condition to the above equation, A = 0.

$$\left[\frac{d\delta}{dt}\right] = \sqrt{\frac{\omega_0(P_m - P_e)}{2H}} * \sqrt{\delta} \qquad \dots (5.18)$$

5.6.1 Natural Frequency of Oscillation of Power System

In this section the natural frequency of rotor angle oscillation of the equivalent synchronous generator connected to the power system through transmission lines is analysed. The synchronous machine is represented with its classical model. The details of equivalent synchronous machine and typical power system disturbance for analysis is as follows.

Base Value	-	190 MVA
Rated Capacity of Equivalent Generator	-	190 MW
Equivalent Inertia Constant (H)	-	3.272 MWs/MVA
Disturbance from Wind and Solar	-	0.6 p.u.

Let us assume that the equivalent generator is initially in steady state. Therefore, the characteristic equation of swing can be written as in equation 5.19 (Kundur, 1994).

$$s^2 + \frac{K_D}{2H}s + \frac{K_S\omega_0}{2H} = 0 \qquad \dots (5.19)$$

Where,

K_S	-	Synchronizing torque coefficient in per unit torque / rad
K_D	-	Damping torque coefficient in per unit torque / per unit speed deviation
H	-	Inertia constant in MWs / MVA
$\Delta\omega_r$	-	Speed deviation in per unit
$\Delta\delta$	-	Rotor angle deviation in elec. rad
s	-	Laplace operator
ω_0	-	Rated speed in elec. rad/s
ΔT_m	-	Change in mechanical torque to synchronous machine, Nm
ΔT_e	-	Change in electrical torque of synchronous machine, Nm

Therefore, the undamped natural frequency oscillation can be written as in equation 5.20 (Kundur, 1994).

$$\omega_n = \sqrt{K_S \frac{\omega_0}{2H}} \text{ rad/s} \qquad \dots (5.20)$$

ΔP_e - The composite load after frequency change, MW

ΔP_L - Non-frequency sensitive load change, MW

D_0 - Load damping constant, MW/Hz

Δf - Frequency change in the power system, Hz

$D_0 \Delta f$ - Frequency Sensitive load change, MW

6.3.1 Derivation of Load Damping Coefficient (D)

The per unit representation of equation 6.25 can be obtained by dividing the equation 6.25 by the base value for power of the power system ($P_{System\ Base}, MW$).

$$\frac{\Delta P_e}{P_{System\ Base}} = \frac{\Delta P_L}{P_{System\ Base}} + \frac{D_0}{P_{System\ Base}} \quad (\Delta f) \qquad \ldots(6.26)$$

$P_{System\ Base}$ - The base value of the power in MW

$$\overline{\Delta P_e} = \overline{\Delta P_L} + \overline{D_0}(\Delta f) \qquad \ldots(6.27)$$

$\overline{\Delta P_e}$ - Total load change in the power system in per unit

$\overline{\Delta P_L}$ - Non-frequency sensitive load change in the power system in per unit

$\overline{D_0}$ - Load damping factor in (per unit)/Hz

The equation 6.28 can be written by rearranging the term of frequency sensitive load change in equation 6.27 and adding the term of rated frequency of the power system.

$$\overline{D_0}(\Delta f) = \overline{D_0} * f_r * \left(\frac{\Delta f}{f_r}\right) \qquad \ldots(6.28)$$

Where,

f_r - Rated frequency of the power system (base value for frequency) in Hz

According to the definition, the expression for the load damping factor, ($\overline{D_0}$, per unit/Hz), can be expressed as in equation 6.29.

$$\overline{D_0} = \left(\frac{\Delta P / P_{System\ Base}}{\Delta f}\right) \qquad \ldots(6.29)$$

Where,

ΔP - Frequency sensitive load change in the power system in MW

By substituting the expression derived for per unit load damping factor in equation 6.29 to equation 6.28, it follows:

$$\overline{D_0}(\Delta f) = \left(\frac{\Delta P / P_{System\ Base}}{\Delta f}\right) * f_r * \left(\frac{\Delta f}{f_r}\right) \qquad \ldots(6.30)$$

By rearranging the terms of equation 6.30 and multiplying 100% the both numerator and denominator, it follows:

$$\overline{D_0}(\Delta f) = \left(\frac{\left(\Delta P / P_{System\ Base}\right) * 100\%}{\left(\Delta f / f_r\right) * 100\%}\right) * \left(\frac{\Delta f}{f_r}\right) \qquad \ldots(6.31)$$

$$\overline{D_0}(\Delta f) = D * \left(\frac{\Delta f}{f_r}\right) \qquad \ldots(6.32)$$

Where,

$$D = \left(\frac{\left(\Delta P / P_{System\ Base}\right) * 100\%}{\left(\Delta f / f_r\right) * 100\%}\right) \qquad \ldots(6.33)$$

D – Percentage change in load for one percent change in frequency

According to the definition of per unit system, the frequency deviation in per unit can be expressed as in equation 6.34.

$$\left(\frac{\Delta f}{f_r}\right) = \overline{\Delta f} \qquad \ldots(6.34)$$

Where,

$\overline{\Delta f}$ - The frequency deviation in per unit

Substituting to equation 6.34 to equation 6.32:

$$\overline{D_0}(\Delta f) = D * (\overline{\Delta f}) \qquad \ldots(6.35)$$

$$\Delta\omega_r = 2\pi(\Delta f) \qquad \ldots(6.36)$$

$$\omega_0 = 2\pi f_r \qquad \ldots(6.37)$$

By dividing equation 6.36 by equation 6.37 the result shown in equation 6.39 can be obtained.

$$\frac{\Delta\omega_r}{\omega_0} = \frac{2\pi(\Delta f)}{2\pi f_r} \qquad \ldots(6.38)$$

$$\overline{\Delta\omega_r} = \overline{\Delta f} \qquad \ldots(6.39)$$

According to the equation 6.39, it is obvious that the per unit frequency deviation is equal to the per unit speed deviation of the synchronous generator. Hence, equation 6.35 can be written as in equation 6.40.

$$\overline{D_0}(\Delta f) = D * \overline{\Delta\omega_r} \qquad \ldots(6.40)$$

By substituting the equation 6.40 to equation 6.27, it follows:

$$\overline{\Delta P_e} = \overline{\Delta P_L} + D * \overline{\Delta\omega_r} \qquad \ldots(6.41)$$

Where,

$\overline{\Delta P_e}$ - Total load change in the power system in per unit

$\overline{\Delta P_L}$ - Non-frequency sensitive load change in the power system in per unit

D - Load damping constant (Percentage change in load for one percent change in frequency) in per unit.

By substituting equation 6.41 to equation 6.24: