Impact of Increasing Renewable Energy Sources on Power System Stability and Determine Optimum Demand Response Capacity for Frequency Control

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***Abstract*— In the last years, renewable energy sources have been increasing more and more over the world because of their benefits as environmentally friendly, clean, and abundant. But this increase led to new problems, for instance, low inertia, unstable supply, and strong estimating necessity. Therefore, power system operators and researchers consider and look for new solutions to these issues. In this study, first, the inertia of a power system under increasing RES capacity is investigated, and the effect of low inertia conditions on frequency stability is shown. Then, it is presented that frequency control with demand response can be successful by determining the optimum demand response capacity with meta-heuristic methods on the same power system.**

Keywords*— *Low inertia, Renewable Energy Sources, Frequency Control, Optimum Demand Response.

I. INTRODUCTION

Traditionally, power system stability is ensured by synchronous machines connected to the grid. They are automatically reacted with its their stored kinetic energy to a sudden power imbalance, such as additional severe load or a loss of generation unit. However, the power systems are forced to change from conventional generation to renewable energy sources (RESs) because of the main reasons as fossil fuels and climate changes [1], [2]. The load-frequency control structure, even though there are some special regulations according to the countries, basically defined by ENTSO-E is shaped by different processes and periods at specific time ranges. Ancillary services of frequency regulation; are frequency containment reserve (FCR), frequency restoration reserve (FRR), replacement Reserve (RR), ensuring to adjust the generation/load unbalance, and restore nominal grid frequency [3]–[5].

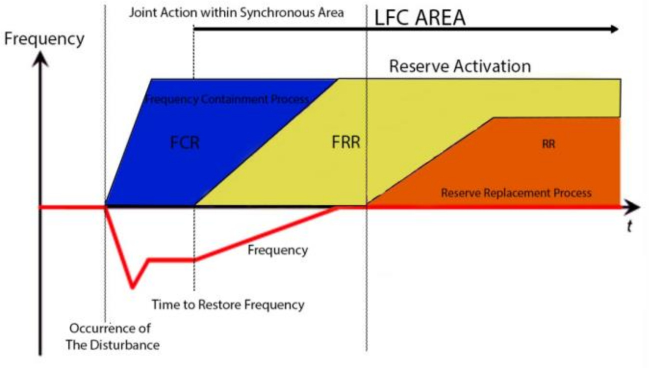

Fig.1. Load-Frequency Control Process[5]

All power plants in charge of the FCR participate equally in the synchronous area and they must be sustained at least for 15 min until FRR and RR are serviced in order.

In Turkey, it has notably developed in increasing RESs through supportive government policies in the last ten years, especially solar, wind, and geothermal. The renewable generation capacity has nearly tripled, and its share in total power generation reached 44% in 2019. The rate of wind and solar electricity generation was only % 1,4 in 2010, it reached nearly % 13 in 2021. Much of this growth is due to 4.3 (GW) of wind and 6.4 GW of solar capacity over the past five years. Compared to the 6.5% level five years ago, wind and solar energy today account for 18.6% of the total installed power [6], [7]. Also, it aims to total of 56,8 GW installed capacity based on RESs including 10 GW in solar, 11,8 GW in wind, 32 GW in hydro, 2,8 GW in biomass, and geothermal in 2023 [8]. Turkey approved the regulation of Paris Climate Agreement in 2021, accordingly, it has made a zero carbon commitment until 2053, like other countries. In this context, it is expected to start energy transition policies by becoming de-carbonized in the energy field. This will speed up electrification by increasing electric vehicles in the transport sector. Also, in order to supply the increasing electricity demand, fossil fuels will be phased out and the RESs will be increased more. The need for grid flexibility can be increased with energy storage and demand-side management applications in addition to hydroelectric and natural gas. As RES capacity increases, traditional frequency control providers may be insufficient and will be replaced by novel applications that respond faster response [9]. Demand side management is the capability to control loads of users to switch on and off or change their consumption related to the system stability. It could be a more reliable method than traditional methods to apply faster balancing between demand and supply [10]. We have classified the applications of demand-side management in power systems: energy efficiency services, price response, peak shaving, regulation response, and spinning reserve, which of these are peak shaving, regulation response, and spinning reserve are directly related to grid stability. Especially spinning reserve and regulation response are the key arguments for frequency regulation of power systems, which comprises the fastest responding control algorithms (real-time demand response-DR) to external signals or local measurements compared to other strategies [11].

This study aims to the effect of increasing RESs on power systems is shown for Turkey since it has RESs capacity increase plans for the next years. Therefore, the grid

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equivalent inertia calculation is firstly calculated by considering the increasing RESs capacity in the generation profile. Then, to show the impact of low inertia on the frequency stability is analyzed by creating a multi-source load frequency control model of Turkey's grid. According to the results, it has been observed that it will be adversely affected by the increasing RESs. Secondly, in order to ensure the frequency control ability of the grid under increasing RES conditions, optimum demand response capacity and control are proposed using meta-heuristic methods. It has been revealed that DR can provide effective benefits in increasing RES conditions when the results obtained on the discussed different scenarios are examined.

II. Motivation And Problem Formulation

A. *Inertia of Power System*

The synchronous inertia of a power system, which is its natural response to a frequency change resulting from a supply-demand imbalance, is related to the rotating speed of the synchronous machines in the grid operation. When the grid frequency decreases, the active power increases with the rotating speed, and decreases under the opposite conditions. Basically, the inertial response of synchronous generators is calculated with kinetic energy. The kinetic energy (E_{kin}) of the rotational mass of the system is determined according to Equation (1). However, we can express the relation between the frequency change of the grid and the generator moment of inertia with Equation (2).

$$E_{Kin} = \frac{1}{2} j w^2 \ (s) \tag{1}$$

$$\frac{dw}{dt} = \frac{T_{gen} - T_{load}}{J_{gen}} \tag{2}$$

where being T_{gen} -synchronous generator torque, T_{load} - total grid load and losses, J_{gen} - grid inertia (kg.m2), and ω/t the change of rotational speed of machine in unit time (rad/s). The coefficient of inertia (H) of a generator is commonly defined as the ratio of the kinetic energy that the generator can store at synchronous speed to the apparent power value. The inertia coefficient of a generator is shown in Equation (3) [12]–[17]

$$H = \frac{1}{2} \frac{J w_n^2}{S_n} = \frac{1}{2} \frac{J\left(2\pi f_0\right)^2}{S_n} = \frac{E_{kin}}{S} \ \text{(s)} \tag{3}$$

The total equivalent inertia coefficient or equivalent total kinetic energy of all generators operating simultaneously in a network is determined according to Equation (4) according to the generator inertia coefficient and apparent power. Thus, all synchronous sources are reduced to an equivalent rotating mass with an equivalent inertia [18]–[20]

$$H_{grid} = \sum_{i=1}^{n} \frac{H_i S_i}{S_{grid}} = \frac{E_{kin_{grid}}}{S_{grid}} \tag{4}$$

H_{grid} is the total equivalent inertia coefficient of the grid, H_i is inertia constant of each *i th* generator connected to the grid, S_i is apparent power of each *i th* generator connected to the grid, S_{grid} is total generator apparent power connected to the grid, E_{kin_grid} is total kinetic energy of the grid. Similarly, the inertia coefficient of the generators in a grid can be calculated according to the source types, thus source-based models can be made in grid analysis. Accordingly, the equivalent inertia coefficient calculation for the same source type is shown in Equation (5). The standard values for H for the synchronous machine are between 2 s to 10 s. [21].

$$H_j = \sum_{i=1}^{n} \frac{H_{ji} S_{ji}}{S_{j_{total}}} \tag{5}$$

H_j is the equivalent coefficient of inertia calculated according to the source type j, H_{ji} is inertia constant of each *i th* generator in the j source type in operation connected to the grid, S_{ji} is the apparent power of each *i th* generator in j source type in operation connected to the grid, S_{j_total} is total generator apparent power of source type j connected to the grid. According to synchronous generators producing at the same operating time, in case of sudden active power change (e.g., generator interruption, significant load loss and system split), the frequency change of the grid can be calculated according to the change in the kinetic energy stored in the rotating masses of the generators. The oscillation relationship between the H_{grid} and df/dt is in Equations (6) and (7). According to these equations, while H_{grid} decreases, the df/dt increases [22], [23]. ΔP is the active power change, f_0 is the nominal frequency, *df/dt* is the frequency change per unit time.

$$2H \frac{df}{dt} = P_m - P_e \tag{6}$$

$$\Delta P = \left(\frac{\left(2 H_{grid}\right)}{f_0} \right) \left(\frac{df}{dt} \right) \tag{7}$$

In this study, the effect of increasing renewable energy sources on the power system, that is, the effect on the total inertia potential of the grid is discussed mathematically. For this purpose, the equivalent grid inertia constant was calculated in the increasing renewable energy conditions of the Turkish grid, and the frequency variation of the grid under changing conditions was examined.

B. *Frequency Response Model of The Grid*

The frequency response of a power system could be considered as a single machine with a centralized load model. To reduce the power system to a basic equivalent model, we could use only the average frequency behavior with the dynamic performance controlled by a separate governor by integrating the individual speeding up power[24] It is shown a basic model of the load frequency control (LFC) loop in a single area power system in Figure 2 [25]

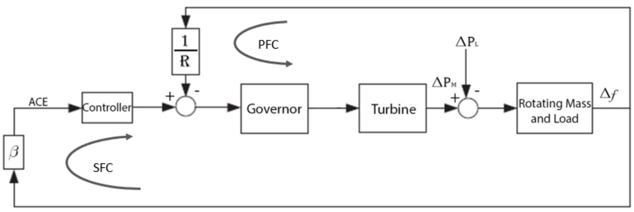

Fig. 2. LFC model of a single area power system

The system swing equation is derived from Equation (7), as in Laplace form in Equation (8) for frequency control.

$$\Delta P_m(s) - \Delta P_L(s) = \frac{\Delta f(s)}{2H(s) + D} \quad (8)$$

The main purpose of the LFC is to reduce the overall deviation of the frequency as soon as possible with the need of power to bring the nominal grid frequency back to the desired value. Frequency characteristics of power systems are made according to source and control structures, and basically LFC models covering single-area, two-area or multi-area connections are studied. In these structures, different types of resources are also considered, which are traditional resources such as hydroelectric, thermal, nuclear.[26], [27]. Frequency deviation (Δf) is evaluated with two parameters: frequency nadir (F_{nadir}) and rate of change of frequency (RoCoF). Frequency nadir states the minimum frequency after any disturbance events, whereas (RoCoF) states the rate at which system frequency declines during the disturbance event [28], [29].

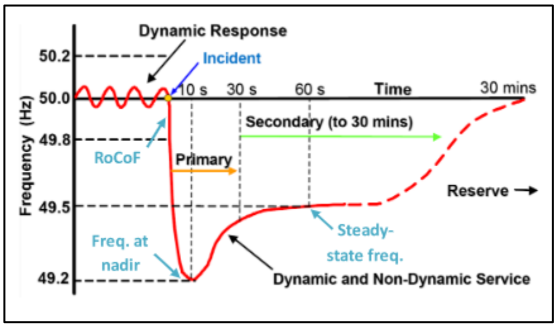

Fig.3. Frequency evolution of the grid after any disturbance event [29]

This study created an equivalent LFC test model of the Turkish grid to examine the effect of increasing renewable energy sources on frequency stability. The conventional resource profile of the Turkish power system mainly comprises coal and natural gas sourced thermal power plants and hydroelectric power plants. Thus, the LFC test model was modeled as a multi-source single are power system that is shown Figure 4.

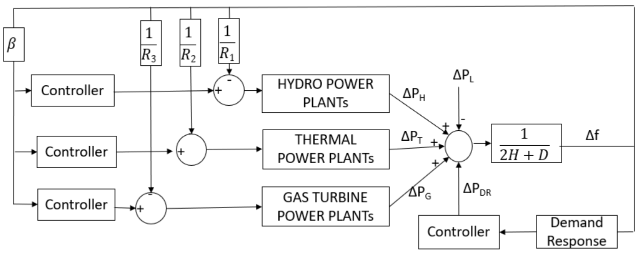

Fig. 4. The equivalent LFC test model of the Turkish grid

C. *Optimum Demand Response (DR) Capacity For Frequency Control*

For LFC, the consumers may measure the grid frequency, and they regulate their loads up and down according to the grid frequency. Thus, they can provide frequency control reserve. This can be defined as demand frequency-controlled reserve, alternatively frequency adaptive power energy rescheduler, dynamic demand, frequency-sensitive appliances, or frequency responsive load controller [30]. Recent studies have shown that demand response can play a more important and effective role in controlling the system frequency in increasing RESs conditions, and it can be the first option, not the last [31]. Unlike the usual, demand response can be used effectively in frequency control with the consumer's participation and the effective controller designs. However, for this, the optimum demand reserve capacity must be known and controlled so that can operate synchronously with the main frequency control methods. In this study, we have presented the effect and benefit of DR in frequency control on the equivalent LFC test model of the Turkish grid, and the optimum DR rate and the controller gains, which are required according to the reaction time setting of the DR, are determined separately with the Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO) algorithms, which have commonly used in LFC. The frequency control swing equation including DR from Equation (8) is given in Equation (9).

$$\Delta P_m(s) - \Delta P_L(s) - \Delta P_{DR}(s) = \frac{\Delta f(s)}{2H(s) + D} \quad (9)$$

III. Case Study Analysis

In this study, the inertia coefficient of the equivalent model for the Turkish grid was calculated according to different RESs participation. Firstly, the reference grid model is handled that is referred to the period of maximum RES participation in that year. Using this data, the total equivalent inertia coefficient of the grid was calculated according to Equations (4) and (5), then the multi-source LFC model was modeled in the MATLAB program in line with the calculated equivalent parameters. According to the RESs participation, the frequency change of the grid was analyzed by considering the probability of load unbalance ($\Delta P_{L=}$ 10%). The effect of decreasing the grid's inertia on frequency control is shown in Table I and Figure 4.

All analysis is implemented on the MATLAB 2018 version that is utilized on a laptop with Intel Core i7-1165G7, 2.8 GHz of speed and 16 GB of RAM. For a correct evaluation of the algorithms' results, they are run using the same population size and the number of search agents, which are selected as 50 and 50 respectively.

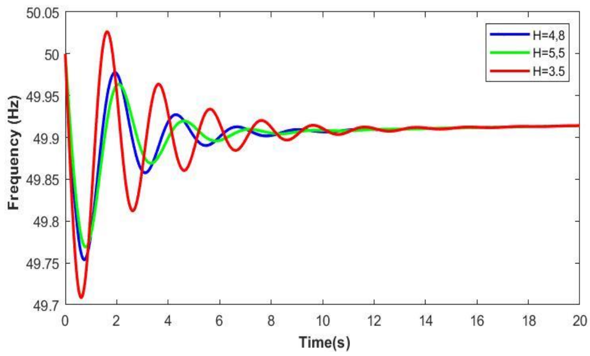

Fig. 5. Frequency Deviation According to Inertia

The increase in RES capacity causes low grid inertia and larger frequency deviations according to the results. While for %20 RESs participation frequency deviation and RoCoF 0,23 Hz and 0,289 Hz/s, for %50 RESs participation they are

0,28 Hz and 0,483Hz/s. In particular, the increase in RoCoF will make frequency control more difficult under sequential fault conditions.

TABLE I. THE TOTAL EQUIVALENT INERTIA COEFFICIENT OF THE GRID ACCORDING TO RES PARTICIPATION

RES Participation (%)	H_{grid}	F_{nadir} (Hz)	RoCoF (Hz/s)	Δf (Hz)
20%	5,5	49,768	0,289	-0,232
35%	4,8	49,754	0,337	-0,246
50%	3,5	49,708	0,483	-0,281

In order to provide frequency control support by DR under increasing RESs conditions, optimum DR capacity and controller gains according to frequency change ratio are determined by PSO and GWO methods. The set point of DR is set as in 200 mHz setpoint, which corresponds to the primary frequency control reserve range for the Turkish grid. This DR method can be considered for emergency frequency controls. Also, PI controller is used for DR controller where Kp and Ki are the PI controller gains, respectively.

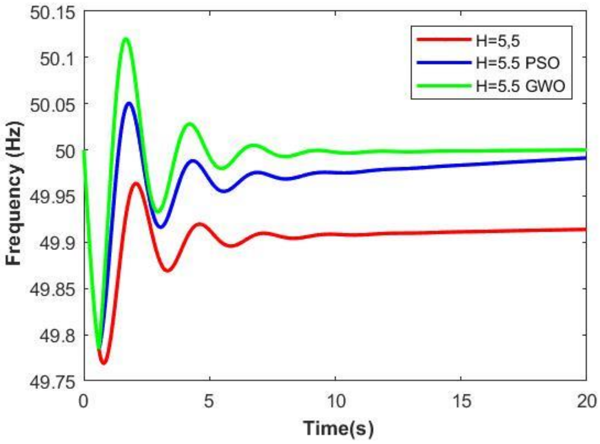

Fig. 6 Frequency Deviation Using DR, H= 5.5 s

Optimum DR capacity is determined as a percentage for three different inertia cases, which were determined sequentially according to the RESs participation.

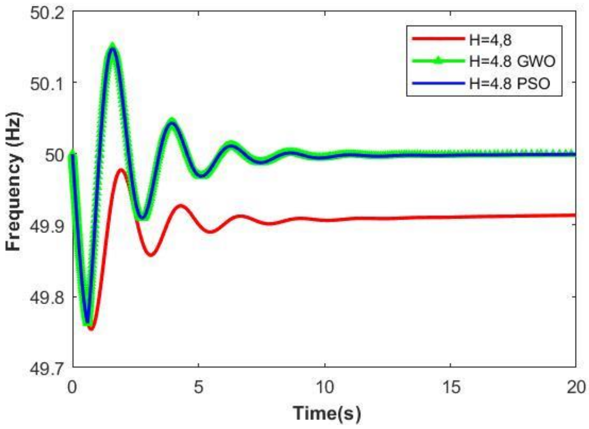

Fig. 7 Frequency Deviation Using DR, H= 4,8 s

The Figures 6, 7 and 8 show the results of frequency control with DR. The optimum DR capacity determined separately using PSO and GWO is given in Table II, and PI controller gains in Table III.

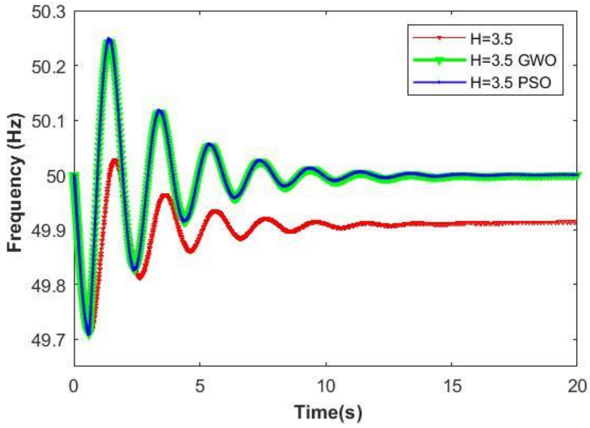

Fig.8 Frequency Deviation Using DR, H= 3,5 s

When comparing before and after DR, it is seen that the frequency change is limited, and the frequency reaches the nominal values. The performance of both algorithms used is successful, but the optimum DR capacities determined are different from each other.

TABLE II. THE RESULTS OF OPTIMUM DR CAPACITY FOR FREQUENCY CONTROL

H_{grid}	Method	F_{nadir} (Hz)	Overshoot (Hz)	Δf (Hz)	*DR* (%)
5,5	PSO	49,784	0,05	-0,216	2,8%
	GWO	49,784	0,12	-0,216	4,7%
4,8	PSO	49,762	0,149	-0,238	9,3%
	GWO	49,762	0,148	-0,238	5,1%
3,5	PSO	49,710	0,248	-0,290	4,9%
	GWO	49,710	0,242	-0,290	4,7%

TABLE III. THE PI CONTROLLER GAINS

H_{grid}	Method	Kp	Ki
5,5	PSO	-1,986	-0,0543
	GWO	-1,925	-0,0054
4,8	PSO	-1,005	-0,002
	GWO	-1,852	-0,004
3,5	PSO	-1,999	-0,002
	GWO	-1,995	-0,004

CONCLUSION

In summary, in this study, it has been shown that increasing RES reduces the flexibility required to ensure grid stability, and the optimum capacity calculation and control has been made for DR, which is one of the flexibility applications. Firstly, the power system of Turkey will have low grid inertia with increasing RESs in the future, and its frequency control capability will decrease. Therefore, it will need new methods such as storage, DR that can increase the grid flexibility. It has been seen that the frequency control with DR on the equivalent LFC model created for the Turkey's grid is successful. It has been seen that the frequency control with DR on the equivalent LFC model created for the Turkish network is successful. When the obtained results are compared, it is seen that large frequency changes can be prevented with DR under increasing RES conditions. However, in this study, we only focused on applying DR with a fixed set point to for emergency frequency control, and different DR methods must be applied to reach definitive results.

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