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Frequency Regulation in Power Grid with Solar PV and Energy Storage

Fasina E.T.[1], Adebanji B.[1], Oyedokun J.A.[2]
[1]Department of Electrical and Electronic Engineering, Ekiti State University, Ado Ekiti, Ekiti State, Nigeria
[2]Department of Engineering and Scientific Services, National Centre for Agricultural Mechanization, Ilorin, Nigeria.

Abstract—*There is a growing demand for renewable energy generation in power grids driven by targets for electricity production from renewable energy resources and environmental concerns. This large-scale integration of variable renewable generation has many challenges for grid operators. This paper proposed a flywheel storage system for effective integration of solar PV system into the Nigerian hydro-thermal power grid and for frequency. Different scenarios for the Nigerian power system in 2030 assuming different levels of future demand and technology availability.*

Keywords— *Frequency regulation, flywheel storage system, inertia, renewable energy sources, solar photovoltaic system.*

I. Introduction

Nowadays, renewable energy sources (RES) are considered as a viable replacement for conventional generation (Crespo et al., 2012). This trend is driven by targets for electricity production from RES, environmental concerns and the desire for increased fuel diversity. High presence of RES may affect the dynamic characteristics of power system in a different way compared to that of the conventional generators (Sebastian et al, 2012; Kenny et al., 2005; Fasina et al, 2015; Liang, 2017). There is need to maintain a balance between generation and demand for power system stability. But renewable energy sources like solar and wind cannot provide this balance due to their intermittent nature (Fasina et al.,2020). Most renewable sources do not provide inertia, which is critical for regulating the system frequency (Milano et al., 2018; Yosef et al., 2021). For example, solar PV is non-synchronous and does not store kinetic energy. Therefore, replacing conventional sources with solar PV will reduce system inertia which increases the magnitude of frequency excursions (Li et al, 2018). This inertia reduction could increase the Rate of Change of Frequency (ROCOF) of the power system leading to load shedding (Jayawardena et al., 2012). When the imbalance between generation and demand is low, frequency deviations become severe which can affect relay operation, and eventually lead to a blackout. It is a necessary requirement to maintain power grid operating frequency within specified limits to assure stable and safe operation (National Grid, 2016).

The results from these past studies show that high penetration of renewable energy generation will affect power system stability (Wu et al. (2013); Fasina et al., 2015 (Alquthami et al. (2010)). However, Energy storage systems (ESS) are considered as one of the most viable options to improve frequency stability. In view of power system frequency stability challenges, several recent works study the integration of RES and energy storage systems in the Israeli power grid (Kottick et al., 1993); Navon et al., (2020). According to Ye et al. (2009); Li et al., (2018); and Sebastian et al. (2012), flywheel energy storage system is a good solution as it has such merits as high efficiency, long life and no environmental pollution. In Nigeria, the Federal Ministry of Power set a target of 30% renewable generation installation by 2030 (Fasina et al, 2017). The Nigerian power industry is considering using solar PV resources to meet the mandatory renewable generation target. The PV technology gained popularity due to the decline in the price of the photovoltaic module. This reduction in cost is mainly due to competition among the manufacturers. This paper investigates the Nigerian power system with high PV penetration and suggest flywheel storage system as viable solution for enhancing power system dynamics. This paper is organized as follows. Section 2 gives the description of the Test system and reaseach methods. Section 3 gives the benefit of storage system in frequency stability management. Finally, the conclusions of this paper are presented.

II. Frequency Regulation In The Nigerian Power System

Frequency control in the Nigerian grid rely on spinning reserves and the inertia of large synchronous machines as it is being practice in most power systems worldwide. Whenever there is loss of a large generation unit, the inertia of the synchronous machines acts to prevent the frequency rate-of-change. In Nigeria, an average 5% of generation capacity (220MW) is reserved for frequency control. When the frequency of the power system is high, the power supply is reduced. However, the power supply is increased when the frequency is low. That means the spinning reserves respond in a matter of seconds to provide more power, and restrain the frequency deviation. In case of extreme deviations, for example when the frequency falls below 49 Hz, under-frequency load shedding is executed. The power grid experienced inadequate governor controls, low generation, and outdated transmission lines (Samuel et al, 2014). Thus, the system experience unnecessary stress and load shedding. This load shedding is carried out manually and is characterized by unavoidable human error (Vanfretti et al, 2010). Frequency deviations are majorly caused by frequent load shedding and sudden loss of generation, load loss, and transmission line trip. In Nigeria, the grid must be kept within +/- 0.4% by the system operator.

Solar PV integration requires careful considerations in areas of solar component production, installations and operation. PV generations must be interconnected effectively onto the power grid. Interconnection of PV to the grid requires an in-depth understanding of the impact on the grid at various points (El-azab et al., 2020). It is essential that the solar PV technical requirements must be met in terms of voltage, frequency, and a reasonable ability to withstand abnormal system operating conditions.

A. Flywheel Storage System

Flywheel energy storages system (FESS) can store electrical energy in kinetic energy form in its rotating mass (Arani et al., 2016). For any storage system, the energy and power limits are major constraints. The kinetic energy stored in a flywheel is given in Eq. (1).

$$E_k = \frac{1}{2} I\omega^2 \qquad (1)$$

Where E_k is the kinetic energy stored in the flywheel, I is the moment of inertia and ω is the angular velocity of the flywheel. The moment of inertia for any object is a function of its shape and mass (Sebastian, 2012). Fig. 1 showed the structure and components of a flywheel storage system.

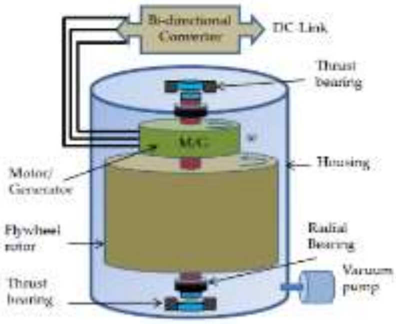

Fig.1. Structure and components of a flywheel (Amiryar et al.,2017)

III. MATERIALS AND METHODS

A. Interconnected Power System

Fig. 2 is a two-area power system. Each area is represented by a voltage source and an equivalent reactance. It has two equivalent generating units connected by a tie line with reactance X_E. Equation (2) is the real power transfer over the tie line.

$$P_{12} = \frac{|V_1||V_2|}{X_{12}} sin\delta_{12} \qquad (2)$$

Where $X_{12} = X_1 + X_E + X_2$, and $\delta_{12} = \delta_1 - \delta_2$

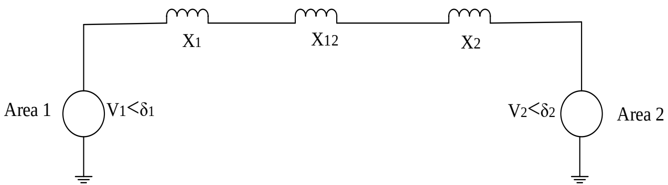

Figure 2 Equivalent network for two-area power system (Bevrani, 2014).

With a small deviation in the tie–line flow ΔP_{12} from the nominal value, i.e.

$$\Delta P_{12} = \frac{dP_{12}}{d\delta_{12}} |\delta_{12_0} \Delta\delta_{12} \qquad (3)$$

$$\Delta P_{12} = P_s \Delta\delta_{12}$$

Where P_s is the slope of the power angle curve at the initial operating angle and

$\delta_{12_0} = \delta_{1_0} - \delta_{2_0}$ (Synchronizing power coefficient)

Thus, we have

$$P_s = \frac{dP_{12}}{d\delta_{12}} |\delta_{12_0} = \frac{|V_1||V_2|}{X_{12}} cos\Delta\delta_{12_0}$$

$$\Delta P_{12} = P_s(\Delta\delta_1 - \Delta\delta_2)$$

If $\Delta\delta_1 > \Delta\delta_2$, the power flow from area1 to area 2

B. Description of the Test System and Research Approach

The test system is a Nigerian power system consisting hydro and thermal generation connected by tie-line as shown in Fig. 3. Nigeria national grid comprises of 132 kV and 330 kV circuits and substations. The hydro generations stations are located in the northern part of Nigeria (at Kainji, Jebba and Shiroro) while the thermal generation stations are located in the south of the country, generally near to the source of gas. The network parameters are given in Table 1 and Table 2. The model of the Nigerian two-area system is developed in MATLAB Simulink environment and are assumed to be operating at the nominal frequency of 50 Hz. \

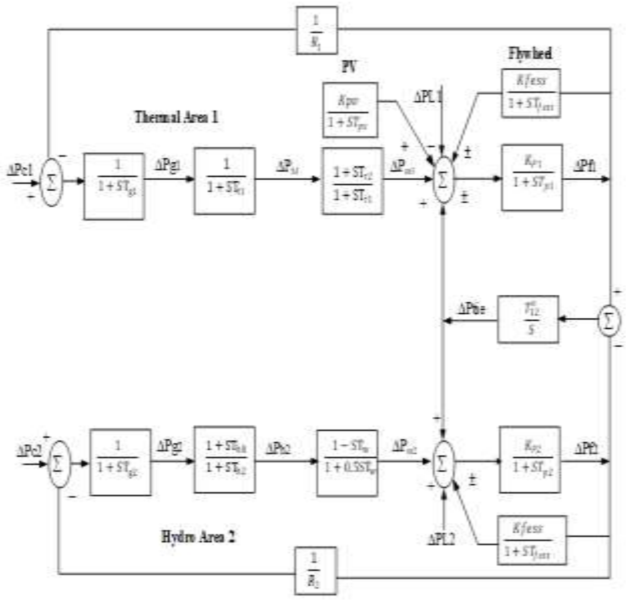

Fig. 3. Two-area power system with PV and storage.

TABLE 1. System parameter (Aliyu et al. 2004).

Areas	Parameters
Area 1 (thermal)	T_{gi}=0.59s; T_{t1}=0.4s; T_{r1}8s; T_{r2}=3.2s; R_1=2.6Hz/pu MW; K_{p1}=130Hz/pu MW; H_1=6.5s &T_{tie}=0.245 B_1 =0.425
Area 2 (hydro)	T_{g2} =0.51s; T_{hR}=10s; T_{h2}=50s; T_w=1.7s;R_1=2.24Hz/pu MW; K_{p2}=112Hz/pu MW; &B_2=8s; B_2=0.425

TABLE 2. Peak and off-peak generation

Area	Peak generation (MW)	Off-peak generation (MW)
Area1	3592	2895
Area 2	1232	680
Total	4824	3575

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IV. Case Studies

Three case studies are presented for investigating frequency regulation in the Nigerian power grid.

- Case study 1 represents the existing power system without PV penetration.
- Case study 2 represents the grid network in year 2030 with PV penetration.
- Case study 3 investigates the impact of flywheel storage system (FESS) on the test system.

The simulations were carried out in a MATLAB Simulink environment. A generation loss of 220 MW ($\Delta P_{G(loss)}$) is used for the simulation. The disturbance was assumed to happen in the thermal area after 10 seconds. Random variations of solar isolation were considered in the simulations. All losses are assumed to be zero and the conversion efficiency of PV generator is assumed to be unity. In addition, it is assumed that FESS have enough storage capacity to accommodate generated power. In the first case study, the existing power system was considered without PV generation. The generation loss of 220 MW was applied after 10s. In the second case study the behaviour of the network model with large scale PV generation was investigated. The inertia of the system is computed by using the Eq. (6).

$$H_{eq} = \sum_{i}^{N} H_i * \frac{S_i}{S_{area}} \quad (6)$$

as provided in (Muhssin et al., 2016), where:

- H_i is the equivalent inertia constant for each power plant,
- S_i is the power rating for each power plant,
- S_{area} is the total power rating for the current area, and
- N is the number of power plants.

In order to meet the rising load demand, PV generation was connected in the network. The load supply was assumed to increase by 2.35% annually. The simulation parameters for FESS are given in Table 3.

TABLE 3. Change in equivalent inertia with PV penetration

Parameter	K_{PV}	T_{PV}	K_{fess}	T_{fess}	FESS (MW)
Value	1.0	1.8	-0.01	0.1	1200

V. Result And Discussion

A. Case Study 1

The simulation results are shown in Fig. 4. The frequency dropped due to the generation loss of 220MW and the power outputs ΔP_{m1}, and ΔP_{m2}, increased providing their primary frequency response at 49.94Hz. This response was enough to supply the load and the frequency stop dropping. Equation (3) showed the change in mechanical power in each area and is given by $\Delta P_{m1} = -\frac{\Delta F_1}{R_1}$, and $\Delta P_{m2} = -\frac{\Delta F_2}{R_2}$. Thus, the generation in the thermal area increases by 197.4MW and hydro area by 53MW at the new operating frequency of 49.988 Hz. That is, 53MW flows from the hydro area to the thermal area.

The result showed that the stored kinetic energy in the conventional generators could not compensate the variations in electricity output from PV generation.

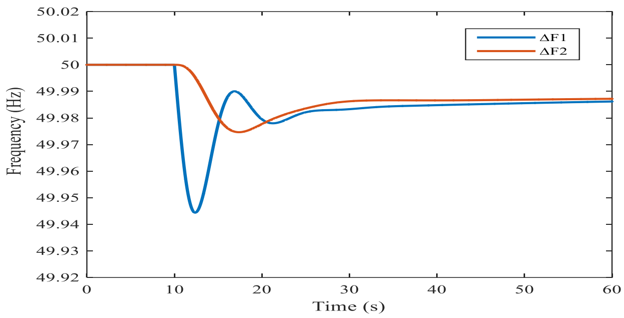

Fig. 4. Frequency deviation step response of thermal and hydro areas.

There is a need for either network upgrade or energy storage technology to support the intermittency of PV output. However, due to lack of fund and the present economic recession, network upgrade is not feasible. This research used flywheel storage system to support the PV generation by injecting the amount of required energy to the power system whenever there is disturbance. Flywheel energy storage can store up to 500MJ of energy and is characterized by high-power density and low environmental impact. Flywheels peak power range from kilowatts to gigawatts and high response time.

Case Study 2

The frequency deviation response in the thermal area dropped from the nominal value of 50Hz due to generation loss of 220MW at t = 10s, as shown in Fig 5. While the frequency deviation in the hydro area is as shown in Fig.5. This drop in frequency is caused by increase in load demand and was highest at 30% PV penetration. operation.

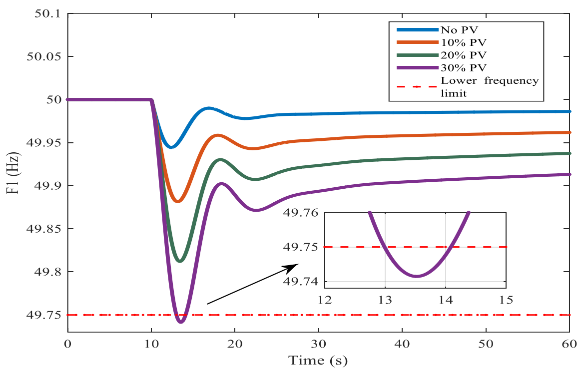

Fig. 5. Variation of frequency nadir without FESS

At the value of the equivalent inertia has reduced to 3.86. That is at 30% PV penetration, the new operating frequency was below the safe operating limit of 49.75Hz (red dashed line in Fig. 5). Also, in the hydro area, the frequency response F2, dropped from nominal value but falls within safe operating limit of the power system as shown in Fig. 5. The summary of the results is presented in Table 4. A suitable control strategy will assist in load–generation balance to maintain frequency at safe.

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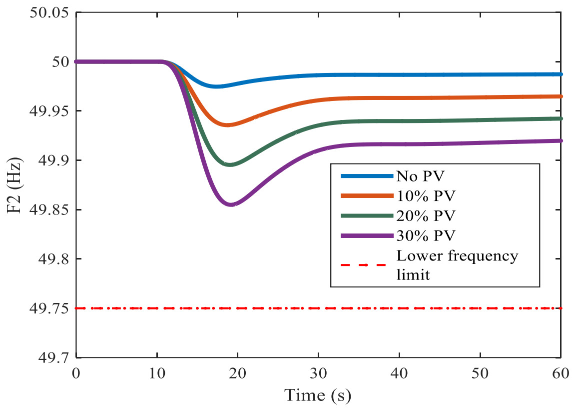

Fig. 6. Frequency deviation step response in hydro area

TABLE 4. Summary of the frequency deviation in the thermal area

Year	PV penetration (%)	Operating Frequency (Hz)
2020	-	49.94
2023	10%	49.88
2027	20%	49.81
2030	30%	49.74

B. *Case Study 3*

The impact of FESS on frequency regulation is investigated in this case study. The storage systems will discharge its stored energy during peak hours and recharge during off peak hours. The variation in the inertia due to PV generation is shown in Table 5. The applied storage system reduced the drop in the system frequency with reduced undershoot as presented in Fig. 7. The operating frequency of the system due to generation loss is 49.741Hz. However, when FESS is connected in the network, the operating frequency increase to 49.753Hz as shown in Table 6. The rise in frequency is due to the use of FESS in the system to complement the PV system. FESS provides a faster response in the power system. Speed limiter help to prevent either the shortage or the surplus of energy store in the FESS.

TABLE 5. Change in equivalent inertia with PV penetration

Year of Simulation	2020	2023	2027	2030
Equivalent Inertia(Heq)	6.50	5.62	4.74	3.86
PV installed (%)	-	10	20	30

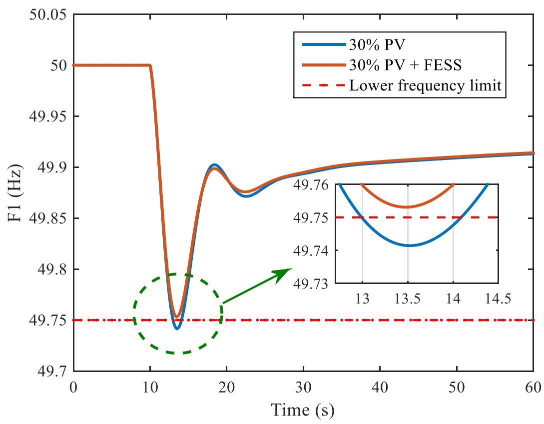

Figure 7 Variation of frequency nadir without FESS

TABLE 6: New operating frequency with and without FESS

	Operating frequency (Hz) Without FESS	Operating frequency (Hz) With FESS
$\Delta F_1(Hz)$	49.74	49.75

VI. Conclusion

The increase penetration of renewable energy sources has necessitated the need to study their impact on the electricity grid. It is essential to provide a suitable control measure to mitigate the impact of renewable generation on frequency support. An increasing penetration of variable renewable generation such as PV increases risks of frequency excursions and higher RoCoF within power systems which can pose serious challenges for frequency stability. This paper proposed using flywheel storage system for managing frequency under high penetrations of large-scale PV, where less system inertia is available. The results obtained in this study showed that the reduction in the overall system inertia due to renewable generators cause the frequency to drop far beyond safe operation of the system. However, the flywheel storage system was able to restore the frequency to a safe value. Flywheels has the advantages of high-power density, low environmental impact, short recharge time and ability to provide active power compensation. However, with the support of FESS the possibility of 30% PV penetration is possible in the Nigeria power network. The research results will enable the Power utility companies, investors, and policymakers in the power sector to make more informed decisions on solar PV-Grid integration.

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