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OPERATIONAL RESILIENCY AND CARBON REDUCTION THROUGH GTG-BESS INTEGRATION

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ABSTRACT

As the variable energy sources become predominant in the energy mix, carbon reduction, power system stability and resiliency have become the topics of prime research. Grid connected and Island systems face similar challenges for multiple applications like frequency control, economic dispatch, peak shaving, black start or spinning reserve. We have studied an Islanded Microgrid application consisting of BESS (Battery Energy Storage System) and Gas Turbine Generator (GTG) system used for Spinning Reserve application. In this paper we present integrated architecture of Hybrid Power System and determine the control algorithm for such operation. We ascertain the response time for the power system, ensuring there is enough spinning reserve available on the grid for smooth operation of the plant and in turn this leads to a reduced carbon foot print operation. Later these results are verified through theoretical framework of Rate of Change of Frequency (RoCoF) and physical testing in Hardware in-the-Loop simulation (HIL).

1. Introduction

In cases when an energy unbalance occurs in the power system the frequency deviates from its nominal value. A large deviation of frequency is expected to occur as the unbalance grows, thus, threatening normal power network operation. With the intention of confining deviation extension to safe levels, frequency surveillance and corrective actions are performed by conventional generators along with grid operator supervision – known as primary control and, if necessary, authorizing spinning reserve release – known as secondary control[1]. Spinning Reserve for frequency control is defined as energy source that is on line, connected and ready to dispatch in seconds to maintain the frequency of the network.

Spinning reserve is a mandatory grid code requirement in almost all power generation applications. To illustrate the application and use of the research idea, we have considered a typical LNG (Liquefied Natural Gas) plant installation with 5 x Taurus 60® gas turbines generator sets, rated at 5 MW, supplied by Solar Turbines®

operating in an N+1 configuration to ensure there is enough spinning reserve to pick up the generation if a Gas Turbine (GT) shuts down. N+1 configuration ensures there is always one hot standby unit available to pick up the load if any operating unit trips. This need to provide a spinning reserve results in the gas turbines operating at a lower efficiency than desired.

The goal of this paper is to introduce energy storage and change the operating philosophy from an N+1 to an N+BESS (Battery Energy Storage System). This will allow the turbines to operate at a higher efficiency point and consume less gas whilst emitting less Carbon Dioxide (CO2) per unit load. An integrated GT + BESS hybrid solution provides enhanced operational flexibility, significantly reduces the thermal stress on a gas turbine; with a positive effect on service life [2].The control algorithm is developed such that the BESS will provide intermittent power if a loss of generation occurs.

2. System Design

Figure 1 illustrates the basic control architecture of the LNG processing plant. On-site power generation system comprises five (5) Taurus 60® gas turbines with a site rating of 4.0 MW each. Each BESS module is rated for 1 MW, 0.5 hour each, total four such BESS modules are used in this configuration making it 4 MW x 0.5 hour system. Each gas turbine has an off-skid control system and all the turbine I/Os are directly wired back to the main turbine control panel. The BESS utilizes PLC based Turbotronic5® as the control system. It comprises of on-skid I/Os controlled by a Multi-Unit-Controller located in the Control Room. Both the BESS and GTs are connected to the Load Shedding Panel via ethernet and data switch. The control objective is to optimize the onsite generation, detect a loss of generation event and discharge the energy storage system, maintaining the grid stability; thus avoiding system black out.

Since the maximum plant load is 12 MW, 4 Units are normally operated at 3 MW capacity in load sharing mode, this is shown in Figure 2 below. If one unit trips the remaining units share the load until Spinning Reserve unit is brought into operation. As the Non-Spinning unit starts participating in load sharing the N+1 backup is not available and only means of avoiding blackout will be through plant wide Load Shedding scheme. Load shedding is not a preferred operation since it impacts the production of the plant.

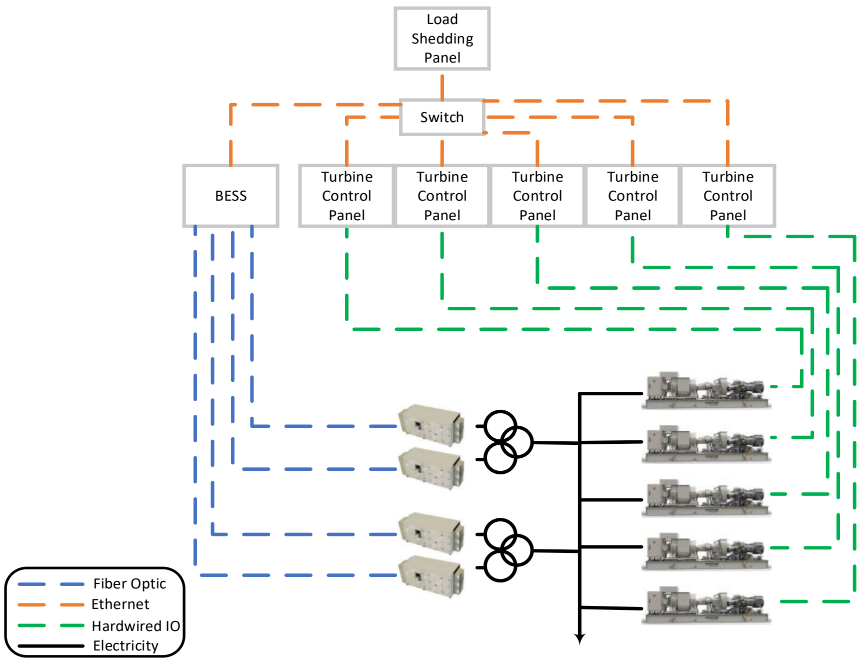

Figure 1: . High Level Control Architecture

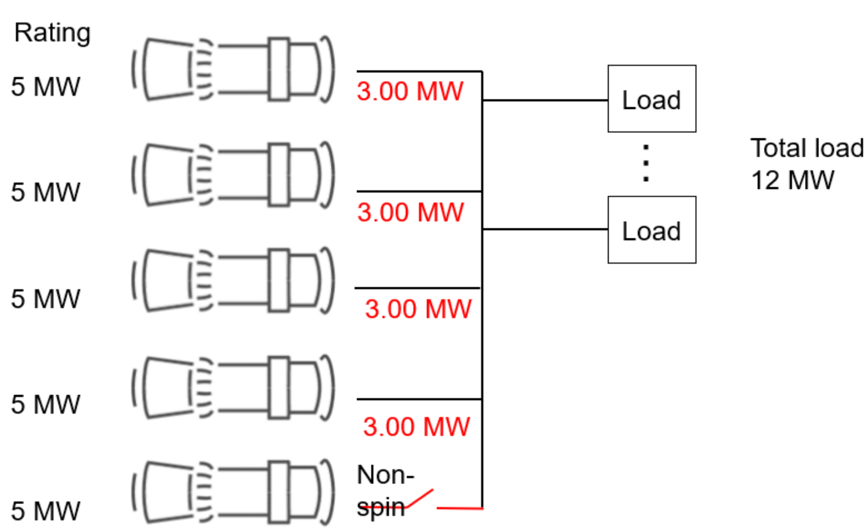

Figure 2: Upon loss of one Generator remaining three units will start sharing the load, non-Spin unit will be deployed in load sharing scheme

In the proposed Hybrid Power System shown in Figure 3, Three (3) x GTG units are operating at their full capacity, BESS is deployed upon Gas Turbine trip, and it starts participating in Load Sharing. It's noteworthy, since most of the Gas Turbines are operating at their full capacity, they have better operational efficiency & lower emissions. Here, we can retain Spinning Reserve capacity for plant and one Gas Turbine can be kept as an installed spare thus reducing the operational expenses.

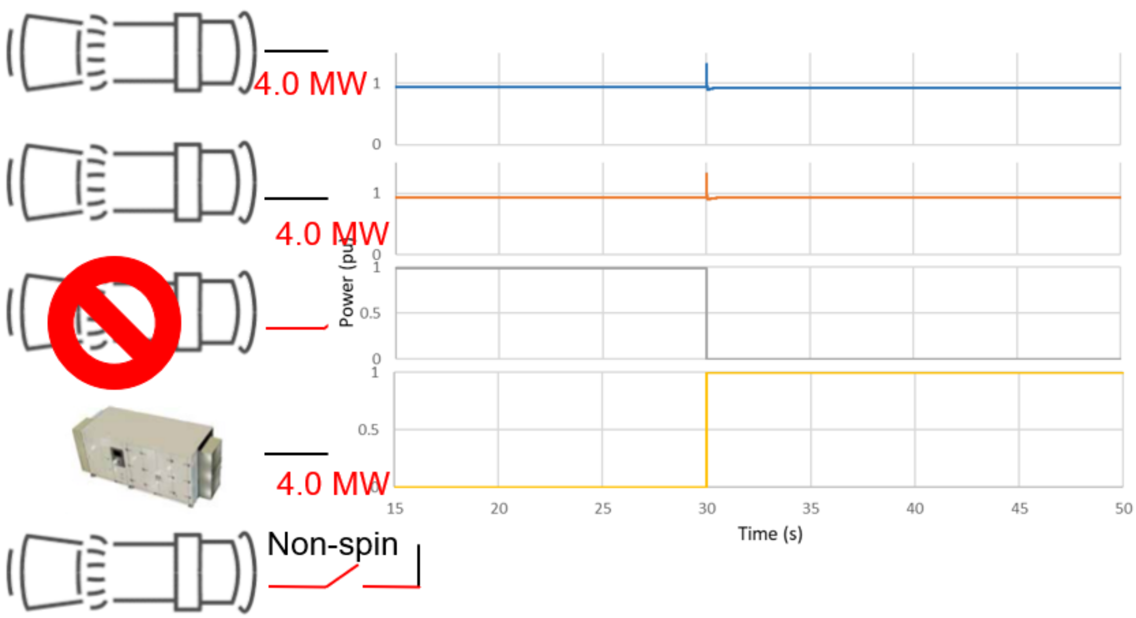

Figure 3: Upon loss of one GTG, BESS will start dispatching the power to the load and remaining two units will start sharing the load, non-Spin unit remains available as Spinning Reserve

SYSTEM OPERATION

1. Start-Up Condition

Under normal start up conditions, it is assumed the BESS is connecting to a powered bus. In this instance, the upstream breakers will be closed, and the BESS inverter will automatically detect the voltage, frequency and sync to the bus.

2. Normal Operation

Under normal conditions, the energy storage system is connected and running online. The system will be optimized to maintain at least 30 minutes of charge time. BESS will be occasionally charging/discharging to ensure the correct state of charge (SoC). This charging/discharging current should not exceed 40kW per unit. Each gas turbine will be loaded up to 90% load as this will allow for any small disturbances to be managed by the gas turbines and avoiding charging/discharging the batteries.

3. Loss of Generation

The BESS system will monitor the following signals:

i. Closed Status of GTG breakers x 5
ii. Open Command from GTG to GTG breakers x 5
iii. On-Line Status of GTG
iv. Power Output of GTG
v. Power Factor of GTG
vi. Spinning Reserve of GTG
vii. Exhaust (T5) Temperature of GTG
viii. Based on these signals, the BESS unit will determine the dispatch control. The opening of the GTG breakers will have the longest detection time and hence recommended to be hardwired. The GTG breaker status will not be true until after a command is sent to the breaker and the breaker fully opens. Method of detection of loss of turbine generator will be a hard-wired loss of breaker closed status signal from the generator breaker aux contact, and hard-wired breaker open command signal from GTG. Either of these events will trigger a BESS dispatch.

4. KW/KVAR Dispatch

As shown in Figure 3, on loss of turbine generator, the BESS will immediately dispatch power to keep plant spinning reserve above a minimum threshold. Initially the amount of power discharged by the BESS will correspond to the magnitude of real power being produced by the lost turbine generator immediately before loss, after a user configured time (e.g., 30 seconds), the BESS will ramp down so that the total plant spinning reserve is equal to the minimum spinning reserve threshold. Whenever possible, reactive power will be produced to maintain a 0.9 PF. The kVar amount discharge will be based upon a 0.9 power factor. Based on the BESS capability curve, the BESS has the most capability discharging at this power factor without reducing the kW capability.

5. Recharging

After a BESS dispatch event, and after another turbine generator is brought online, the BESS will use the excess spinning reserve to recharge to be ready for another event. BESS can either act as a fixed load and charge at a constant power, or act as a variable load and maintain a fixed plant spinning reserve. The recharge time will be dependent on the amount of energy required to be fully charged and the available power to charge it. The charge rate will be 4MW and this will ensure a fully discharged battery is fully charged in 30 mins. However, it is unlikely that the BESS will ever be charged at 4MW as this would require an entire GTG.

CONTROL ALGORITHM AND SIMULATION

Hybrid Power System control philosophy is focused on the entire system rather than just the energy storage, it has 4 key aspects:
(i) Calculating Rate of Change of Frequency (RoCoF)
(ii) Optimizing the onsite Distributed Energy Resources (DER)
(iii) Detect a loss of generation
(iv) Discharge DERs before the system black out.

Following sections describe the concept and calculation of RoCoF followed by a test setup environment that allows for testing of this algorithm on an efficient system architecture.

1. Inertia (H) & Rate of Change of Frequency (RoCoF)

As the amount of kinetic energy from the generators spinning masses lowers, the system becomes more prone to disturbances resulting in power imbalances, which leads to severe frequency deviations and a higher rate of change of frequency (RoCoF), reaching 6 Hz/s in extreme cases[3]. As shown in Figure 4, during normal operation, the frequency fluctuates around the nominal value due to load variations. This leads to the mismatch between mechanical and electrical torque, causing change in the generator rotor speed (and, therefore, activating inertial dynamic response)[4]. System ability to address these constant changes in the power balance is defined by system inertia (Hsys), which is dependent on the inertia constants (Hi) of all synchronous generators in the system and system rated power (Ssys). Hi represents the time in seconds a generator can provide rated power solely using the kinetic energy stored in the rotating mass[5] and S is rated power in MVA.

$$H_i = \frac{E_{\text{kinetic}}}{S} \qquad (1)$$

$$H_i = \frac{\text{kinetic energy at rated speed [MWs]}}{\text{rated power [MVA]}} \qquad (2)$$

$$H_{sys} = \frac{\sum_{i=1}^{n} H_i S_i}{S_{sys}} \qquad (3)$$

In conventional power systems, the dynamic behavior of synchronous generators based on the swing equation can be expressed as [6]

$$J_S \frac{d\omega}{dt} = T_m - T_e = \frac{P_m}{\omega} - \frac{P_e}{\omega} \qquad (4)$$

where Js means the moment of inertia, ω means the angular velocity of the synchronous rotor, Tm and Te mean the mechanical and electrical torque for the generator, Pm and Pe mean the mechanical and electrical power for the generator. The inertia power response is usually generated using the stored kinetic energy in synchronous generators. Thus, the kinetic energy ($E_{kinetic}$) of system rotating mass including spinning loads is formed as[4]

$$E_{\text{kinetic}} = \frac{1}{2} J_S \omega_{sys}^2 \qquad (5)$$

ωsys is the synchronous angular frequency.

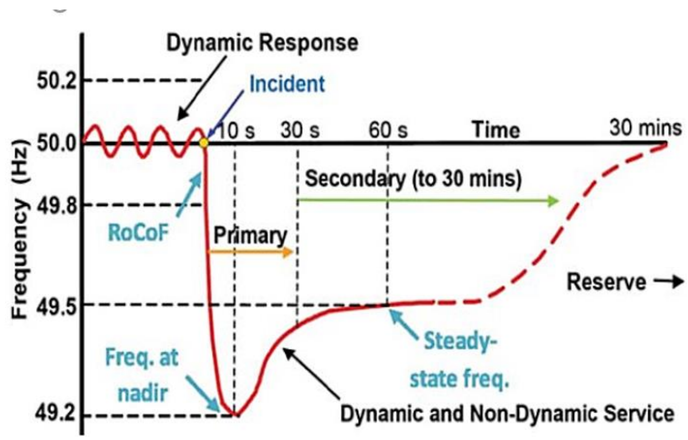

Figure 4: . Dynamic Response of a Grid upon loss of generation

The rate of change of frequency, also known as RoCoF, is a very important variable inside the power system operation and control. The RoCoF has an intrinsic relationship to the magnitude of the power imbalance during the frequency response. As shown in Figure 4 above the RoCoF defines how quickly the generator speed changes and the system frequency changes upon an incident. The RoCoF is expressed in Hertz per second (Hz/s); this might be used as a measure of the severity of a disturbance, it is the initial response to frequency deviations after the disturbance is stabilized by the system inertia (H). If a power system's generation portfolio fully consists of synchronous generators, in case of a notable sudden change in the active power (eg, generator outage, loss of significant load, and system split), RoCoF can be calculated by the change in the kinetic energy stored inside the rotating masses of the machines[7].

$$P_{gen} = P_m - P_e = \frac{d(E_{\text{kinetic}})}{dt} = \frac{d\left(\frac{1}{2}J_S\omega_{sys}^2\right)}{dt}$$
$$= J_S\omega_{gen}\frac{d\omega_{sys}}{dt} \qquad (6)$$

The RoCoF means the time derivative of the frequency signal, which is used to calculate the inertia response of the system as [8]

$$2HS = J_S\omega_{sys}^2 \qquad (7)$$

$$P_{gen} = P_m - P_e = J_S\omega_{gen}\frac{d\omega_{sys}}{dt} \qquad (8)$$

$$P_m - P_e = \frac{2HS}{\omega_n}\frac{d\omega_{sys}}{dt} \qquad (9)$$

$$\frac{2H}{f_n}\frac{df_{sys}}{dt} = \frac{P_{\text{m}} - P_e}{S_{sys}}$$

$$ROCOF = \frac{d(\Delta f)}{dt} = \frac{f_n(P_m - P_e)}{2HS} \qquad (10)$$

As can be seen from the equation below, RoCoF is highly dependent on the system inertia and magnitude of power imbalance ∆P. As we can see smaller inertia value causes higher RoCoF.

$$\text{RoCoF} = \frac{\Delta P f_n}{2H_{sys}S_{sys}} \qquad (11)$$

fn—nominal frequency.

The RoCoF calculation in real environments is a complex process, it is measured and validated in real time data simulated through Hardware In-the-Loop (HIL). HIL is real time simulation technique used by emulating signals from real time embedded systems. Conventional generators were not planned to withstand high RoCoF values therefore, measurements and tests should be carried out to identify the technically feasible limits[9]. The following section explains these tests and the determination of RoCoF which is the key parameter for accurate and tighter control of the Spinning Reserve application.

2. Controller Hardware in-the-Loop (HIL) Simulation

CHIL (Controller hardware-in-the-loop) simulation is a technique where the controller is integrated into the test loop. Signals through sensors and actuators are simulated to test the controller actions, as shown in the test setup shown below. CHIL is leveraged to test algorithms. Most common CHIL tools include dSPACE®, Opal-RT®, Speedgoat®, Typhoon® HIL, ETAS®. For the purpose of this test Typhoon HIL was utilized. To allow for ease of trouble shooting and limited inverter board capacity only 3 x GTG were simulated connected to BESS. Actual PLC based controller with plant specific software was connected in a loop back mode to emulate entire dynamic operating spectrum, from startup, full load to shut-down. 2x50% Inverter control board are used to simulate the inverter operation of grid following and grid forming mode. As shown in the Figure 5 Units are sharing the load and when one unit goes down immediately BESS detects the loss of power and starts dispatching the power thus providing the needed spinning reserve.

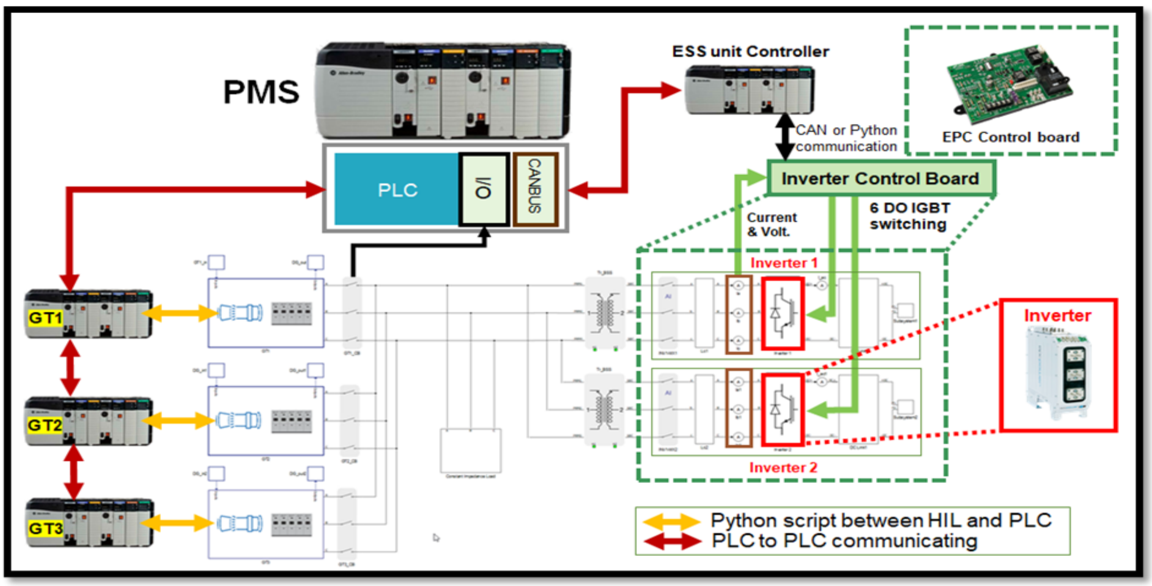

Figure 5: . Controller Hardware In Loop (CHIL) simulation set up using Gas Turbine Generator and Battery Energy Storage System

CONCLUSION

An integrated hybrid Gas Turbine Generator (GTG) system coupled with Battery Energy Storage System (BESS) shifts the operating philosophy from N+1 to a N+BESS system. This hybrid integration, coupled with advanced algorithms described in this paper can reduce capital expenditure (CAPEX) and Operating Expenditure (OPEX) of any system. Such hybrid power systems architecture allows better overall efficiency of the plant and leads to reduced CO_2 emissions. This operation model provides significant savings in carbon footprint of the plant. Table below shows the overall savings due to efficiency and carbon tax.

TABLE I : CARBON FOOT PRINT AND OPERATIONAL COST REDUCTION

Item	Current Configuration	Proposed Configuration	Savings
KW Rating of GT	3 MW each	4 MW	
No of GTs operating	4 Nos	3 Nos	
% of Rated Load operation	75%	100%	
Fuel Consumption mmBTU/hr	40.21	51.1	
Annual Fuel Consumption mmBTU/Yr	345,806	439,460	
Total Fuel Consumption($5 mm/BTU)	1,383,224	1,318,180	
Annual Fuel Cost ($)	$6,916,120	$6,590,900	$325,220
Ton Co2/Yr	80,000 Tons	66,000 Tons	
Carbon Tax (50$ /Ton)	$ 4,000,000	3,300,000	$700,000
Annual Saving (Fuel Cost and Carbon Tax avoidance)			$1,025,220

REFERENCES

[1] E. M. G. Rodrigues, G. J. Osório, R. Godina, A. W. Bizuayehu, J. M. Lujano-Rojas, and J. P. S. Catalão, “Grid code reinforcements for deeper renewable generation in insular energy systems,” *Renew. Sustain. Energy Rev.*, vol. 53, pp. 163–177, 2016, doi: 10.1016/j.rser.2015.08.047.

[2] I. Scott and S. H. Lee, “Battery energy storage,” in *Large Energy Storage Systems Handbook*, 1st ed. New York: CRC Press and Taylor and Francis Group, 2011, pp. 153–178

[3] B. Hartmann, I. Vokony, and I. Táczi, “Effects of decreasing synchronous inertia on power system dynamics—Overview of recent experiences and marketisation of services,” *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 12, Dec. 2019, doi: 10.1002/2050-7038.12128.

[4] M. Kosmecki *et al.*, “A methodology for provision of frequency stability in operation planning of low inertia power systems,” *Energies*, vol. 14, no. 3, 2021, doi: 10.3390/en14030737.

[5] T. Kerdphol, M. Watanabe, K. Hongesombut, and Y. Mitani, “Self-Adaptive Virtual Inertia Control-Based Fuzzy Logic to Improve Frequency Stability of Microgrid with High Renewable Penetration,” *IEEE Access*, vol. 7, pp. 76071–76083, 2019, doi: 10.1109/ACCESS.2019.2920886.

[6] X. Feng, A. Shekhar, F. Yang, R. E. Hebner, and P. Bauer, “Comparison of Hierarchical Control and Distributed Control for Microgrid, Electric Power Components and Systems,” *Electr. Power Components Syst.*, vol. 45, no. 10, pp. 1043–1056, 2017, doi: 10.1080/15325008.2017.1318982.

[7] H. Zhang, H. Sun, Q. Zhang, and G. Kong, “Microgrid Spinning Reserve Optimization with Improved Information Gap Decision Theory,” *Energies 2018, Vol. 11, Page 2347*, vol. 11, no. 9, p. 2347, Sep. 2018, doi: 10.3390/EN11092347.

[8] M. U. Usama, D. Kelle, and T. Baldwin, “Utilizing spinning reserves as energy storage for renewable energy integration,” 2014, doi: 10.1109/PSC.2014.6808136.

[9] H. Bevrani, “Robust Power System Frequency Control,” *Robust Power Syst. Freq. Control*, 2009, doi: 10.1007/978-0-387-84878-5.