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Escuela Académico Profesional de Ingeniería Eléctrica

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Performance Analysis of the Bess System: Contribution to the Primary Frequency Regulation at C. H. Marañon-Huanuco

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Performance Analysis of the Bess System: Contribution to the Primary Frequency Regulation at C.H Marañon - Huanuco

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***Abstract*—** The research aimed to evaluate the Battery Energy Storage System (BESS) system for primary frequency regulation at the Marañón hydroelectric plant. The research approach is quantitative, the method is deductive-descriptive, the type of research that was carried out is applied to a level of descriptive-correlational research and the design was non-experimental with longitudinal cut, frequency data of the system was used compared with the frequency of the speed regulator of the Marañón hydroelectric plant, according to the data obtained another comparison was made with the system frequency and the plant frequency after the installation of the BESS system, finally a simulation of the data obtained is carried out to see the behavior of the batteries during the power contribution time for primary frequency regulation. Concluding that, facing disturbances in the Peruvian power system, the BESS system is a good alternative when it comes to stabilizing the network, with the quick charge and discharge that positively influences the frequency, it was also possible to calculate the percentage of non-compliance that was reduced after the use of the BESS systems together with the economic benefits generated by the use of BESS systems.

Keywords: COES, PFR, SEIN, BESS

I. Introduction

The Economic Operation Committee of the National Interconnected System (COES) the Perú, is a private entity responsible for preserving the security of the Peruvian electrical system, coordinating short, medium, and long-term operations at minimal cost.[1]

Electrical systems tend to be very dynamic, which is reflected in the constant variations in the frequency of the entire system. For this reason, there is a series of complementary services that take care of fixing some unwanted situations that may risk the operability of the electrical system, one of these is the primary frequency regulation, a rapid-action mechanism that establishes an automatic regulation of each generation unit to balance load variations, resulting in the stability of the system's frequency.

Therefore, one of the functions of COES is to establish the criteria and methodology for the determination, assignment, programming, and evaluation of compliance and performance of the rotating reserve of the National Interconnected Electrical System (SEIN) associated with Primary Frequency Regulation (PFR). [2]

According to PR21, which is one of the procedures of COES detailing a series of obligations that all generation units and their owners must face, as well as the response times of speed regulators against primary frequency assignment, it also details the penalties in case of non-compliance with the contribution of secondary regulation to the national electrical system. [1]

Since the beginning of operations, the Marañón hydroelectric plant has been failing to comply with the PFR contribution designated by COES, leading to a series of penalties according to the monthly evaluations carried out by COES. For this reason, the use of BESS systems is considered an alternative solution.

According research on diagnostic analysis and evaluation of storage systems [3], a study on the use of BESS systems for the contribution of rotating reserve is conducted. Therefore, based on this already completed research, the objective is to use battery systems for the contribution of primary frequency regulation, thus reducing the monthly penalties for non-compliance. One of the hypotheses is that the use of BESS systems would positively influence the frequency of the SEIN, and economic benefits would be generated by avoiding the monthly penalties that resultfrom the non-compliance with the contribution of PFR.

II. Materials and Methods

A. Battery Energy Storage Systems

According to [4], they are a set of components that encompass different technologies. The characteristic of these technologies is that they store energy in an electrochemical form. To achieve a broad storage capacity is due to the arrangements inside, whether in series or parallel configuration, always considering the voltage and capacity that these batteries should have. One of the advantages of BESS systems is their ease of installation and they do not have location restrictions for their installation.

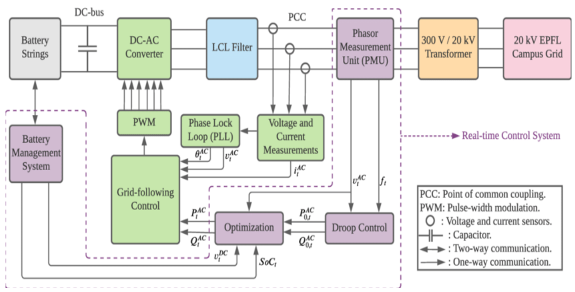

Fig. 1: Schematic Diagram of a BESS System

In Figure 1, we can observe the components of the BESS system, which we will detail below:

- Batteries
- Converter
- Battery management system
- Controller
- Protection systems
- Transformer
- Civil Works

B. Primary frequency regulation

According to [5], primary frequency regulation in a power system is the property of maintaining the system's balance autonomously in the face of variations or disturbances caused by the power supplied relative to the power consumed, which is referred to as the system's own regulation. Generally, this state of equilibrium should be maintained unless there are disturbances in the system that exceed the automation limits programmed in each generating unit. If the system reaches a state that surpasses these limits, an alternative is provided to achieve the balance of generation and load.

The National Interconnected Electrical System (SEIN) is composed of multiple companies from the generation process to distribution. Therefore, frequency is an important parameter for complying with the limits related to the quality of electrical energy. This parameter must be within the operational limits of the power electrical system to prevent instabilities. In this study's case, it would be the Peruvian electrical system. Thus, it is the obligation of every generation plant to have equipment and instruments that automatically act to regulate their production, in order to compensate for the changes in consumption caused by demand. This regulation is known as Primary Frequency Regulation (PFR). Electrical generation machines must operate below their maximum power to have an operational margin to perform frequency regulation; this operational margin is called Spinning Reserve (SR). This allocation of SR will affect the dispatch of the Wholesale Electricity Market (WEM) and consequently the market price (MP) for frequency and power control. [3]

"Primary frequency regulation aims to automatically correct the instantaneous imbalances between production and consumption. It is provided by the power variation of the generators immediately and autonomously by the action of the turbine speed regulators in response to frequency variations." [6]. Frequency regulation is extremely important as it is directly related to quality. This parameter must be within the operational limits so that the system does not experience problems. When these operational limits are significantly exceeded, they can cause a series of damages to the system. For example, motors can operate at different speeds that do not correspond to the characteristics for which they were created. Another example would be clocks that work at frequency; these clocks would have erroneous time values or would either be delayed or advanced. The optimal work of the generators is for all to be working in synchronism with a stable frequency. "Since energy cannot be stored in vast quantities, if the consumed energy increases but the mechanical power contributed by the turbines remains constant, the increase in generated energy can only be achieved with the stored kinetic energy, which implies a reduction in the rotation speed of the generators and the subsequent reduction of the electrical frequency of the network, which is directly interrelated with that speed." [7]

- **Primary frequency control**

The operation of this control is local, and generally, the response time for this operation is between 2 to 20 seconds. Each generator, whether from a hydraulic or thermal source, is limited by the inertia of each generator. Below is an image where you can observe the control equipment that makes up the system, in relation to the equilibrium state represented by the 60 Hz frequency of the Peruvian electrical system, which can be seen in Figure 2.

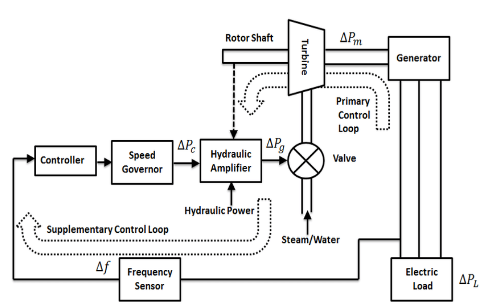

Fig. 2: Main elements of a synchronous generator in

frequency control.

- **Generator transfer function**

A synchronous generator consists of the shaft-turbine assembly that rotates under two opposing torques: The first is the mechanical torque Tm and the electromagnetic torque Te , the former tends to accelerate the shaft while the latter tends to slow it down. The equation for this motion would be as follows.

$$J\frac{d^2\theta_r}{dt^2} = (T_m - T_e)$$

Where J is the moment of inertia and θ_r is the rotor angle. It can be written instead of the second derivative in the following way.

$$\frac{d^2\theta_r}{dt^2} = \frac{d\omega_r}{dt} = \frac{d(\omega_t - \omega_{0)}}{dt} = \frac{d\Delta\omega_r}{dt}$$

Where ω_t is the rotor speed, ω_0 is the reference speed, and $\Delta\omega_r$ is the speed deviation, with that data we can write the following equation.

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{J}(T_m - T_e)$$

If the nominal power is the base power S_base, the reference frequency as the base frequency ω_base, and the base pair would be T_base, we can perform the division between both terms to obtain the unit values, leaving the equation as follows.

$$\frac{d\Delta\omega_r[pu]}{dt} = \frac{1}{2H}(T_m[pu] - T_e[pu])$$

H would be the inertia constant, and the equation would be

$$H = \frac{\frac{1}{2}J\omega_{base}^2}{S_{base}}$$

The inertia constant H is a parameter widely used in the control of electrical systems and represents the kinetic energy accumulated in the axis of the synchronism speed divided by the base power. [8]

We express the variables in unit values and the equation would be as follows.

$$\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}(T_m - T_e)$$

The magnetic torque is difficult to measure, that's why the equation is better expressed in terms of power instead of torque. The relationship between power and torque would be 〖P=ω〗_r T, in this sense we can write.

$$(\Delta P_0 - \Delta P) = (\omega_0 + \Delta\omega_r)(T_0 - \Delta T)$$

- **Balance between demand and generation**

Generation and load are directly related to the frequency in a power electrical system. All electric power generators operate in synchronism, meaning that the rotation frequency of each of them multiplied by the number of pairs of poles is precisely the system frequency (60 Hz). [8] While there is a steady state, the torque applied in each turbine on each synchronous generator is equal, discounting losses, to the electromagnetic torque that tends to brake the machine. If at a given moment the load increases, or in other words, the demand for energy increases, consequently, the electromagnetic torque in the generators increases, as a consequence these are braked, and the system frequency decreases.

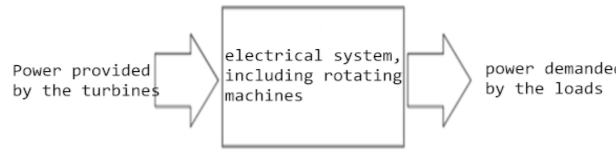

Fig. 3: Energy balance in an electrical system.

Another way to represent the balance between demand and generation would be by comparing the mechanical power that enters a system with the electrical power consumed by the loads. This comparison would be equal if we consider discounting losses. As we can see in Figure 3, if the electrical power consumed by the loads increases, but the mechanical power provided by the turbines remains constant, the increase in demand can only be obtained from the kinetic energy stored in the rotating machines. The reduction of kinetic energy in synchronous generators is equivalent to the decrease in their rotation speed, so the electrical frequency of the system falls. [8]

C. Methodology

Due to the nature of the data that comprise the BESS systems against the primary frequency regulation, there is a need to quantify this relationship, for this reason, the research approach for this study corresponds to the quantitative one. The research method is based on two types, the first is deductive, this method is the deduction of general rules or laws from particular elements and that exceed the content of each of them [9], in the case of the research, the behavior of the energy injection with the BESS batteries and the frequency response for primary frequency regulation will be verified. The second method used is the descriptive one, which is "the type of research that aims to describe some fundamental characteristics of homogeneous sets of phenomena, uses systematic criteria that allow establishing the structure or behavior of the phenomena under study, providing systematic and comparable information with that of other sources" [10].

The research carried out is better suited to the type of applied research [11], because the first step that has to be carried out is the collection of information in this case from the C.H Marañón, either from reports, manuals, and reports, as well as the power and frequency data of each generating unit of the plant, later this information is used to solve the causal relationship of the use of BESS systems against primary frequency regulation with the purpose of solving the problem of non-compliance with the frequency contribution against a deviation of the same in the SEIN.

In the case of this research, the documentary technique is used since the data that will be obtained are found in reports, data records, logbook of the Marañón hydroelectric plant.
On the other hand, the instrument where the frequency and power data coming from the ION meters of each generation unit and all the information found in documentary sources are in the RPF Compliance Record.
The analysis of the data and the processing was carried out in the following informative programs:

- Microsoft Excel
- Matlab
- DigSilent Power Factory

To define the sample, a non-probabilistic intentional sampling for convenience was used, since the selection of the subjects of study does not depend on probability, but on the characteristics of the study and the researcher's criterion based on the directly observed requirement.
The sample to investigate would be the Marañón hydroelectric plant, whose installed power is 19.8 MW.

III. RESULTS

Identification of the connection point for the BESS system

BESS systems have the advantage that they can be installed in the location of one's choice. In this practical case, we have some options for installing the BESS system. The operational areas available at the Marañón plant are the machine house where the three generator groups are located, we also have the Marañón substation where we have the 13.8/60 KV step-up transformer, and finally, there is the Huaricashash substation that connects in turn with the Unión and Huallanca substations. It should be noted that the BESS system can be located at these three points already mentioned, but for a better selection, we must consider other important aspects that are mentioned below:

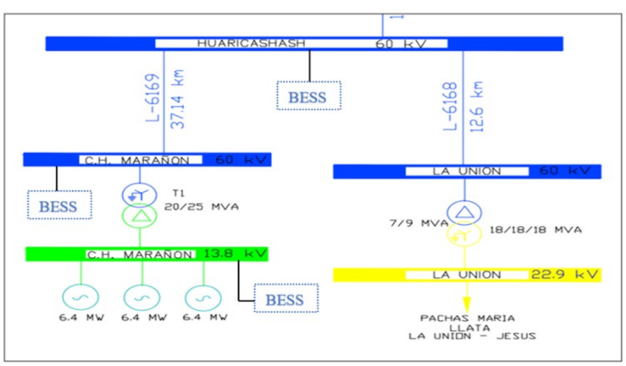

Fig. 4: Possible location of the BESS system.

In figure 4, we can observe the 13.8 kV busbar to which the outputs of the three generators in the plant are connected. These generators are located in the machine room, where personnel are available 24 hours a day. This setup allows for continuous monitoring of operations and a rapid response to significant events in the BESS systems. On the other hand, to connect to the 13.8 kV busbar, a smaller-capacity step-up transformer will be required, making the installation of the BESS system feasible.

BESS system sizing

Table 1 shows the power data for each generating unit of CH Marañón. According to the technical procedure of COES (PR21), the rotating reserve margin assigned to the generation plants is 3.8% relative to the total effective power.

Table 1: Revolving reserve calculation

Generation Groups	Effective power (MW)
UG1	19 MW
UG2	
UG3	
Rotating reserve margin for RPF (3.8%)	0.722 MW

The data obtained from the spinning reserve for the Marañón hydroelectric plant is 0.722 MW. This means that the BESS storage system must be sized with a minimum power of 0.722 MW. However, for the proper execution of the secondary regulation contribution, it is necessary to increase the power margin. Therefore, for the application case, it will be considered that the sizing of the BESS system be 1 MW.

Performance of speed regulators

According to the NTCSE, the frequency is a measure of quality and its parameters must be stable. The nominal frequency is 60 Hz, and it should oscillate within a reference range of ±0.6%, meaning the frequency should be between 59.64 Hz and 60.36 Hz.

To simulate the work of the regulators, information on the frequency was collected over a minimum period to assess behavior in a scenario where the frequency varies constantly. This data was obtained from the ION meters of the Marañón hydroelectric plant. However, before that, we will download the frequency data of the national interconnected electrical system from the COES website to compare the operability and execution of the primary frequency regulation contribution. This information is also useful to identify the periods in which the primary regulation contribution was not met, and consequently, to know the number of non-compliances over a period of time.

In Figure 5, we will present a scenario of a 20 MW load connected to the 60 kV line. This, in turn, produces an imbalance in the system. Therefore, we will observe the behavior of the speed regulator of the CH Marañón in response to this imbalance. The repercussion on the electrical system is as follows:

- After the event is executed, the frequency decreases to a value of 59.804 Hz, due to the action of the generators' inertia.

- Subsequently, the frequency increases in value and tends to recover, this is due to the work of the speed regulators of the generators, and the contribution of the spinning reserve according to PR21.

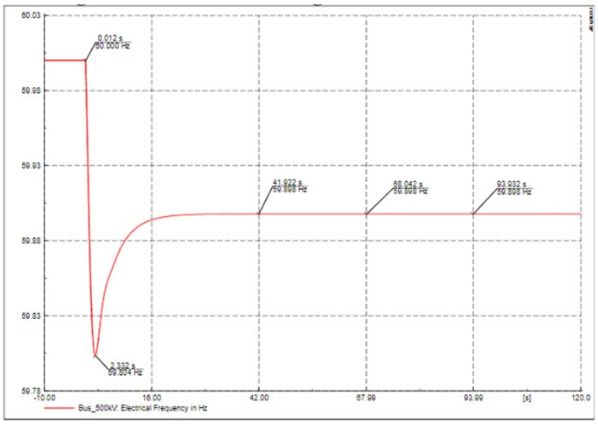

Fig.5: Behavior of the RVH to stabilize the frequency.

Performance of the BESS control system

In the following simulation, a scenario is presented where a 20 MW load is connected to the 60 kV line. This connection produces an imbalance in the system, which is why we will observe the behavior of the BESS control system's performance, in Figure 6.

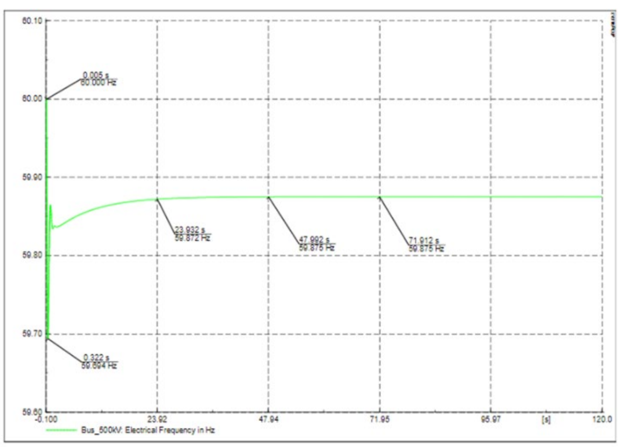

Fig. 6: Behavior of the BESS system to stabilize the frequency.

In this case, the behavior of the BESS system is observed in the same scenario to be evaluated. Consequently, we also take data on the frequency behavior at the time of the BESS systems' operation. Before carrying out the measurements, the primary regulation control of each speed regulator at the Marañón hydroelectric plant is deactivated. Subsequently, frequency data from the ION meter of the plant are collected.

The frequency decreases to a value of 59.694 Hz solely due to the action of the generators' inertia.

Afterward, the frequency increases due to the discharge of the batteries to normalize the frequency state, in accordance with the considerations of PR21. Finally, the frequency begins to stabilize until it reaches an ideal equilibrium point for the system.

Economic benefits from installing the BESS system

One of the benefits of installing BESS systems is the reduction of penalties. The goal is to reduce penalties to a value close to zero. With this scenario, we can say that with the reduction of penalties, this turns into an economic benefit by avoiding the penalty payment for non-compliance with RPF. Another important aspect is that since the BESS systems provide RPF contribution immediately, securely, and without issues, this results in an incentive for the contribution made as indicated by COES, becoming an additional economic income for the generating company. Lastly, we have another economic benefit related to the generation of constant energy without the activation of frequency regulation in the speed regulator. This means that the generation machines would be delivering constant energy without variations because, in that case, the BESS system would be in charge of performing the primary frequency regulation, no longer the speed regulator. Following, Figure 7 shows the aforementioned data.

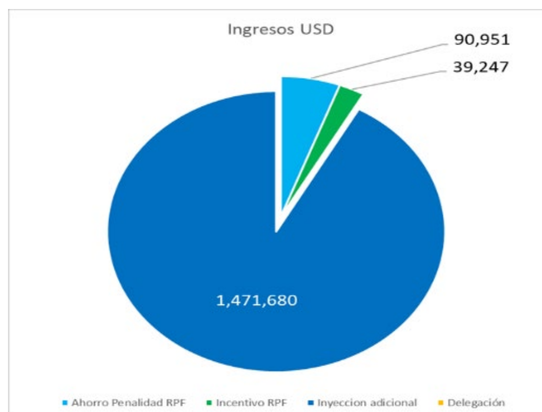

Fig. 7: Economic income from the use of BESS systems.

Discussion of results

In the current research, the general hypothesis proposed is that BESS battery systems have a positive influence on the primary frequency regulation contributed by the Marañón hydroelectric plant. The results obtained in reference to the general hypothesis are that, thanks to the installation of the BESS systems, penalties for non-compliance in the contribution of spinning reserve from the Marañón hydroelectric plant were reduced by 100%. Another favorable aspect for frequency regulation is the response time to load rejections that occur in the national interconnected electrical system. Compared to the response time of the plant's speed regulators, the BESS systems responded in 0.322 seconds. Since they do not have mechanical components, this speeds up the power supply to the system, achieving stabilization in the shortest possible time.

These results are supported by Arturo L. Torres E [3], who in his research titled 'Diagnosis, analysis, and evaluation of battery storage systems for their application in the primary frequency regulation of a combined cycle power plant' [3], indicates that the use of Battery Storage Systems would be a good alternative solution for primary frequency regulation. Thanks to the results obtained by this research, and in the same way that the operability of this system was evaluated, the author carried it out in a combined cycle generation plant with an installed capacity of 567 MW. This is consequently reflected in the sizing of the batteries, which according to his calculations would be 20 MW, considering the energy cushion that must be stored. According to the simulations they conducted, the response time to an event in the SEIN is almost the same as the results obtained in this research, less than 1 second.

IV. Conclusions

- The installation of a BESS battery system at the Marañón hydroelectric plant provides a quick response to frequency deviations in the Peruvian electrical system, compared to the spinning reserve of generators which have a slower response time. Additionally, it generates greater reliability for the use of primary frequency regulation because the BESS systems will be used exclusively for the frequency contribution required by COES.
- The BESS systems' capacity, based on the installed power of the Marañón hydroelectric plant, positively satisfies the power demand and, having an extra power cushion for any contingency, favors the reliable operation of the BESS system and consequently ensures the power contribution for frequency regulation.
- Similarly, with the data obtained from the capacity of the BESS system, the technical characteristics of the inverter installed at the output of the BESS system are determined. These systems contribute to the rapid response for charging and discharging the batteries, featuring a protection system that extends their lifespan.
- With the use of BESS systems, the reduction of penalties is 100%, as these systems would assume primary regulation due to their rapid response. The reduction is significant, which is why the absence of penalties would be an economic benefit for the company. Additionally, there are other economic benefits such as the sale of available energy that was previously not generated due to the margin of restriction of the spinning reserve.
- Thanks to improvements in the regulatory framework, according to the COES procedure, which is PR-21, the creation of projects using BESS systems for primary frequency regulation in Peru is viable.

V. Recommendations

- The use of BESS systems is recommended for all power plants whose energy source is hydraulic, exclusively for primary frequency regulation.
- With the installation of the BESS system, it was oversized for better battery performance; a more detailed study on battery charging and discharging and how they would affect the batteries' lifespan is recommended.
- It is recommended to conduct a more extensive study on critical deviations in the system and the behavior of inverters in response to radical frequency changes.
- An economic benefit calculation was performed, showing the BESS system's ability to reduce penalties. It is recommended to analyze the wear generated on the components of the hydraulic speed regulator during the provision of rotating reserves and compare the wear without the provision of rotating reserves to see the economic benefit generated by maintenance costs.
- It is recommended to review the current regulatory framework to explore the possibility of delegating primary frequency regulation to other power plants, with the aim of diversifying the market for ancillary services in the Peruvian electrical system.

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