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TESIS

Modernization of the Speed Regulator: Benefits for Efficiency and Stability in Electrical Generation - electroperú S.A.

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"Modernization of the Speed Regulator: Benefits for Efficiency and Stability in Electrical Generation - electroperú S.A."

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Abstract: **The research aimed to present an analysis of the technical, operational, and economic benefits obtained by modernizing the speed regulator of a hydroelectric power plant in Peru. The results show that the modernization significantly improved the dynamic response to frequency disturbances, eliminated penalties for regulatory non-compliance, obtained economic incentives for better primary regulation performance, and achieved more efficient turbine operation. In addition, the economic savings and additional income generated by these benefits were quantified, demonstrating that the investment made was an adequate and profitable solution for this type of hydroelectric power plants. Finally, recommendations are made for regulatory agencies and the electricity system operator to promote the modernization of frequency regulation systems in other generating plants, considering the benefits this generates for the stability and reliability of the electrical system.**

Keywords: Speed Regulator, Primary Frequency Regulation, SEIN, Hydroelectric Power Plants.

I. INTRODUCTION

The electric industry faces profound changes globally, driven by decarbonization, digitization, and the decentralization of generation. Technological advances have enabled more efficient and flexible management of electricity supply and demand, leading various countries to reform their electricity sectors [1]. In Paraguay, the electricity sector is of great strategic importance due to its abundant water resources and hydroelectric generation; with the presence of the large binational plants of Itaipu and Yacyretá, the country generates approximately 62,500 GWh of electricity, of which it exported around 50,000 GWh to other countries, mainly Argentina and Brazil, representing about 80% of total production. As for domestic consumption, Paraguay consumed approximately 12,500 GWh, representing a low per capita consumption compared to other countries in the region [2].

Despite having a clean and renewable energy matrix, the Paraguayan electricity system faces challenges in modernization and operational efficiency, particularly in the update of the speed regulators of the hydroelectric power plants, which are fundamental for frequency regulation and the balance between generation and demand. The modernization of these systems can improve operational efficiency and flexibility [3].

An illustrative case of the impact that the lack of modernization of electrical assets can have is that of Colombia. The country has a predominantly hydroelectric power matrix, which in 2022 contributed around 70% of total generation. However, the prolonged drought that affected the country in recent years, coupled with the lack of investment and modernization of hydroelectric power plants, highlighted the vulnerability of the Colombian electricity system. [1]. The rigidity of the speed regulators of hydroelectric power plants, which could not adequately adapt to variations in reservoir levels, triggered an energy crisis that forced the country to significantly increase thermal power generation, with the consequent increase in costs and CO_2 emissions. [2]. This experience demonstrates the importance of maintaining modernized electrical assets that are adapted to the changing conditions of the system, in order to ensure the reliability and efficiency of electricity supply, especially in countries with a high dependence on hydroelectric generation.

In the case of Peru, the country also faces similar challenges and opportunities regarding the transformation of the electricity sector. Peru, like Paraguay, has an electricity matrix with a significant share of hydroelectric generation [1]. In this context, the modernization of the speed regulators of hydroelectric power plants can represent important advantages for the Peruvian electrical system. The new speed regulators of hydroelectric power plants offer advanced monitoring and remote control functions, which improve operational efficiency and safety. This increases the availability and reliability of the hydroelectric generation fleet, which is fundamental for the Peruvian electrical system. By improving the response and control capacity of hydroelectric power plants, they can more effectively complement the generation from intermittent renewable sources, favoring greater penetration of these technologies in the country's energy matrix. The Junín region in Peru is one of the regions with the greatest hydroelectric potential in Peru, with the presence of power plants such as Mantaro, one of the largest in the country. And Cerro del Águila,

The new speed regulators can optimize the use of the water resource, reduce losses and improve the stability of generation. Improved response and control capacity of the hydroelectric power plant allows greater integration of variable sources such as solar and wind in the energy matrix [4]. Modern control systems can contribute to a more environmentally friendly operation, minimizing impacts on ecosystems. Consequently, the main objective is to analyze the technical operational and economic benefits derived from the modernization of the speed regulator in the Mantaro hydroelectric power plant, in order to evaluate the viability and convenience of implementing this type of improvements in other hydroelectric power plants in the national electrical system.

II. MATERIALS AND METHODS

A. Speed regulator system of the hydroelectric power plant.

According to [5] Hydraulic turbine speed regulators are control devices that adjust the fluid input to the turbine to maintain a constant rotational speed despite load variations. These regulators aim to coordinate the operation of the turbines in the interconnected power system to compensate for fluctuations in demand and generation. Hydraulic turbine speed regulators typically consist of a set of valves and servomotors that control the flow of fluid to the turbine.

A key function of these regulators is to limit the large variations in the expected inlet flows in hydroelectric and mini-hydroelectric power plant installations. This is achieved through the use of an electric servomotor as the governor, combined with an advanced controller that incorporates adaptive cross-filtering algorithms, normalized LMS, fuzzy logic, and neural networks.

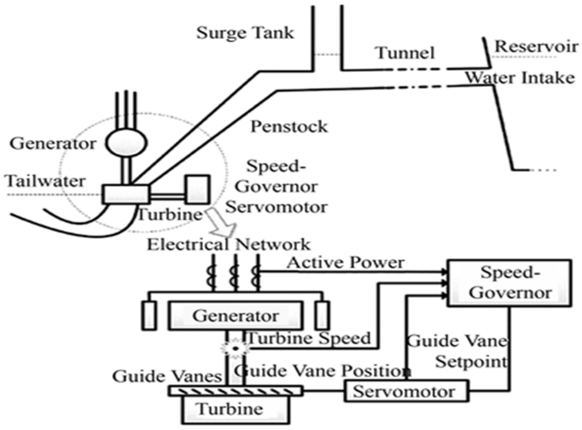

Fig. 1. Typical design of a hydroelectric power plant

Fig 1 shows a schematic diagram of a hydroelectric power plant and its turbine control system. It details the different components of the system and how they interact to generate and regulate energy. Moreover, this diagram shows the flow of energy from the reservoir to the electrical grid, with a control system that dynamically adjusts the operation of the turbine according to demand.

B. Review of Technical Regulations

According to [6] The planning and operation of hydroelectric power plants in Peru are framed within a set of technical standards that regulate various aspects, including those necessary to ensure the stability, security, and reliability of the National Interconnected Electrical System. These standards establish the guidelines and procedures that generating companies must comply with

C. Technical Standard PR21: Technical Requirements for the Operation of Generation Units in the National Interconnected Electric System

The Technical Standard PR21 "Technical Requirements for the Operation of Generation Units in the SEIN" establishes the technical requirements that must be met by the generation units interconnected to the National Interconnected Electric System in Peru, in order to guarantee the safety, stability and quality of the electricity supply. The speed regulators of the generation units must meet the following requirements:

- They must be able to maintain the system frequency within the established ranges in the face of load variations.
- They must have adequate sensitivity and response speed to avoid oscillations and contribute to system stability.
- The parameters of the regulators must be adjusted and tested periodically to ensure their proper functioning.

Additionally, the standard establishes that the generating units must maintain a power regulation capacity that allows them to respond quickly to the requirements of the electrical system, avoiding frequency drops or instability. The implementation of efficient speed regulators in hydroelectric power plants is crucial to guarantee the stability and reliability of the interconnected electrical system.

D. Operation of the speed regulator according to primary frequency regulation

A speed regulator in a hydroelectric power plant operates through a control system that monitors the speed of the turbine rotor and automatically adjusts the opening of the intake gates or valves, with the aim of maintaining a constant frequency in the electrical system.

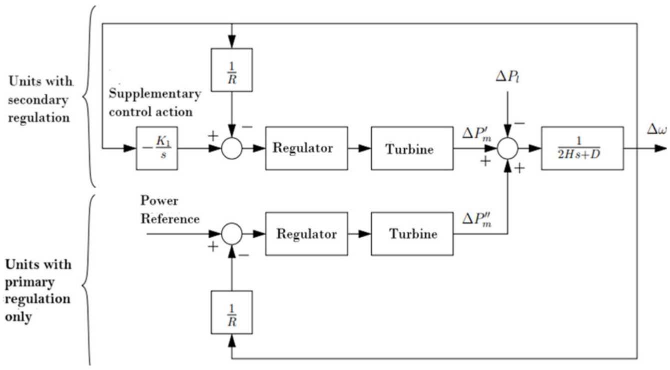

Fig. 2. Automatic generation control based on regulation

As observed in Figure 2, when a load variation occurs in the system, the speed regulator detects the change in frequency and sends a control signal to the turbine mechanisms to adjust the water flow and restore the frequency to its nominal value.

E. Calculation of penalty charge

The PR21-COES [6] procedure will determine the non-compliance fee and its corresponding settlement as follows:

$$\text{CargoINC}_{g,n} = \sum_{j=1}^{D} \left(\text{INC}_{g,j} \times \%\text{RA} \times \text{GenM}_{g,j} \times \text{COR}\right) \quad \text{....(1)}$$

Where $CargoINC_{g.n}$ is the Penalty for non-compliance of Group "g" for month "n". D is the number of days in month "n"., $INC_{g.j}$ Daily non-compliance level of Group "g" detected for the day"j", $GenM_{g.j}$ where the average power of Group "g" on day "j" expressed in MW. This value is obtained by averaging all the power records of day "j", including zero values, COR is the Opportunity Cost of the Non-Supplied Reserve for RPF, determined based on the efficient investment and operation costs of an Equipment for RPF expressed in S/ / MW-day. and finally % RA: Primary Reserve assigned to the Group, determined in the annual study indicated.

The non-compliance charges calculated using the previous formula will be distributed among the Groups whose average monthly compliance with the RPF service exceeds the current value of FaC, using the corresponding formulas.

$$\mathrm{Cumpli_g} = \frac{\sum_{j=1}^{D}\left[\left(1-\%\mathrm{RPNSd_{j,g}}\right).\mathrm{P_{j,g}}\right]}{\sum_{j=1}^{D}\left[P_{j,g}\right]} \qquad \ldots\ldots..(2)$$

- $\mathrm{Cumpli}_g > FaC$, so

$$\mathrm{Incent_g} = \mathrm{CargoIncT_n} \times \frac{\mathrm{Cumpli_g} \times \mathrm{PE_g}}{\sum_{\mathrm{U_{RPF}}} \mathrm{Cumpli_U} \times \mathrm{PE_U}} \qquad \ldots\ldots(3)$$

- $\mathrm{Cumpli}_g \leq FaC$, so

$$\mathrm{Incent_g} = 0 \qquad \ldots..(4)$$

Where Cumpli_g is the monthly indicator of compliance with the RPF service by Group "g". % $\mathrm{RPNSd}_{j.g}$ is the daily average of the percentage of the primary reserve not supplied by Group "g" corresponding to day "j". D is the number of days in the evaluation month. Incent_g is the compliance incentive corresponding to the owner of Group "g". $\mathrm{CargoIncT}_n$ is the sum of the charges for non-compliance of all Groups determined during month "n". PE_g. PE_U is the monthly active energy production of Group "g" or "U". U_{RPF} is all the Groups with the obligation to provide the RPF service that operated in month "n" that meets the $\mathrm{Cumpli}_g > FaC$ condition. $\mathrm{P}_{j.g}$ is the presence parameter of Group "g" on day "j", its value will be one (1) if the Group had operated in any period of the evaluation day, otherwise its value will be equal to zero (0). FaC is the updated compliance factor, this factor represents the average non-compliance level of the last 180 evaluation days available at the time of its update

F. *Balance between demand and generation*

Generation and load are directly related to frequency in an electrical power system. A key aspect to ensure the balance between demand and generation of electrical energy in the Peruvian interconnected system is the adequate regulation of the generators' speed. In accordance with the provisions of the Technical Standard PR21 [6]. The speed regulation systems of the hydroelectric power plants connected to the SEIN must meet certain technical requirements to maintain the stability of the system.

On the one hand, the speed regulation systems must have a fast and precise response to variations in the system frequency, so that they can quickly compensate for imbalances between generation and demand. Additionally, these systems must have an adequate power reserve margin, so that they can assume load increases without causing overloads or instabilities in the electrical system. As established in the Peruvian regulatory framework, non-compliance with the technical requirements of the speed regulation systems can generate economic penalties for generators, which encourages maintaining optimal operation of this equipment [7].

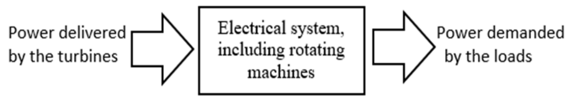

Fig. 3. Energy balance in an electrical system.

Figure 3 shows that 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 a decrease in their rotational speed, which causes a drop in the electrical frequency of the system. Without any corrective mechanism, load variations in the electrical system would cause a system collapse within a few minutes. [7].

Therefore, maintaining frequency control within acceptable parameters ensures a balance between generation and consumption. The control of this balance is achieved through an indispensable element in conventional power generation plants: the governor or speed regulator [6].

III. RESULTS

The modernization of the speed regulator of generator 2 during the year 2023 repeatedly failed to comply with the PR21 regulation of the COES, said group will be the sample in this investigation and the comparison of results will be carried out with generation units 1, 3 and 4, since these units share the same operating conditions of the Mantaro hydroelectric power plant - Electroperu S.A.

A. *Performance of speed regulators based on frequency drop events in the SEIN*

According [6]. to the Technical Standard for the Quality of Electrical Services, frequency is a variable that reflects the quality of the electrical service, so it must be kept within stable parameters. The nominal frequency of the system is 60 Hz, and it must oscillate within a range of ±0.6%, that is, between 59.64 Hz and 60.36 Hz.

To analyze the benefits of modernizing speed regulators, we have collected information from an event where a power plant with considerable power was disconnected from the SEIN. This data, obtained from the ION meters of the Mantaro hydroelectric power plant, allows us to evaluate the system's behavior in the face of constant frequency variations. In addition, we have downloaded frequency information from the SEIN from the COES website, in order to compare the operability and contribution of primary frequency regulation. This information will also help us identify the periods in which the contribution of primary regulation was not achieved and, therefore, know the number of non-compliances during a given period.

B. Analysis of the event before the modernization of the speed regulator.

Event (02/03/2024 05:49:00): The TV generator of the Ventanilla Thermal Power Plant with 128 MW was disconnected due to a failure in the unit's controllers, as reported by ENEL GENERACIÓN PERÚ S.A., the owner of the facilities. As a consequence, the frequency decreased to 59.6 Hz. No supply interruptions were reported. At 10:07 pm, the generator was declared available.

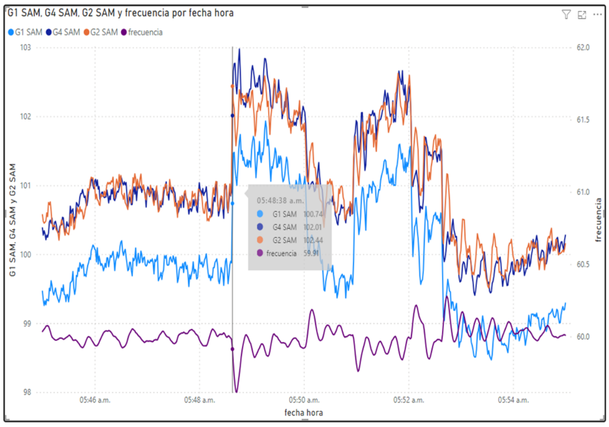

Fig.4. Behavior of G1, G2, G3, G4 to stabilize frequency.

In Figure 4 it is observed that the frequency decreased to 59.6 Hz, a symmetric behavior of G2 with respect to the other groups is observed, G2 took 102.44 MW in response to the frequency drop after 04 seconds it decreases its power due to the frequency recovery of the SEIN, it is evident that G2 does not manage to comply with what is established in PR21.

C. Analysis of the event after the modernization of the speed regulator

Event (31/03/2024 20:42:16): The TV generator of the Chilca 1 Thermal Power Plant was disconnected when it was generating 155.28 MW due to a failure, caused by high vibration in bearing 5 of the generator, as reported by ENGIE, the owner of the equipment. As a consequence, the frequency of the SEIN decreased to 59.55 Hz. At the time of the disconnection, the power plant was operating in a 2x1 combined cycle. No interruption of supplies in the SEIN was reported. The unit was taken out of service for inspection.

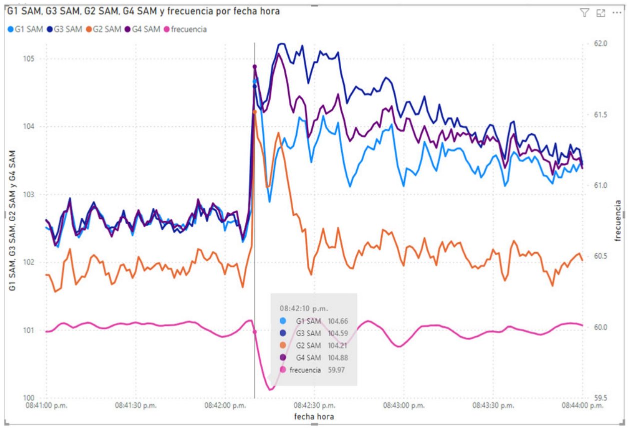

Fig. 5. Behavior of G1, G2, G3, G4 to stabilize frequency.

Figure 5 shows that the frequency decreased to 59.55 Hz, the G2 generator took 104.21 MW, then after 02 seconds its power decreases due to the recovery of the SEIN frequency, the other generators decrease their active power slowly. It is observed that the modernized speed regulator of G2 has a fast and effective response compared to the other generators.

D. Non-compliance and Economic Losses before Modernization of the Speed Regulator.

The modernization of speed controllers offers various economic benefits for generating companies. One of them is the reduction of penalties for non-compliance with primary frequency regulation requirements. By mitigating these penalties, companies achieve significant savings. In addition, improvements in speed controllers help facilitate interaction with operators, generating an additional economic incentive from COES. Finally, frequency regulation in the speed controllers of generating machines represents another economic benefit, as it allows hydroelectric power plants to operate more efficiently. Together, these aspects contribute to improving the economic viability of hydroelectric power plant operations. In this case, we will evaluate the penalties obtained before the modernization of the speed regulator.

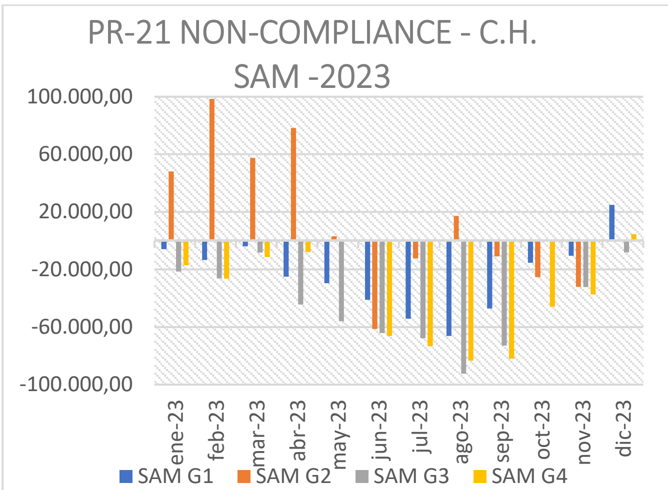

Fig. 6. Behavior of G1, G2, G3 and G4, based on non-compliance with PR21 of 2023

In Figure 6 it was observed that the G2 of the Mantaro Hydroelectric Plant. has the highest values in non-compliance with primary frequency regulation and consequently has the highest penalties, the graph shows that this unit during the year 2023 is not economically profitable with this PR21 regulation.

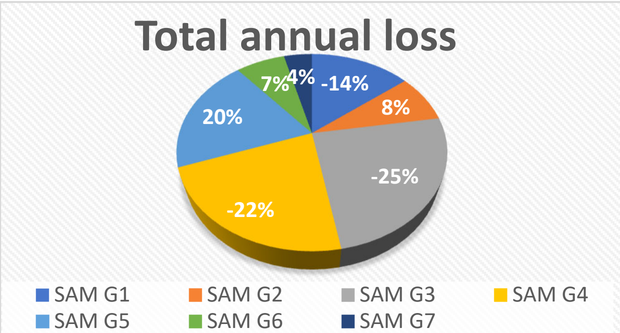

Fig. 7. Total loss of G1, G2, G3 and G4, based on non-compliance with PR21 of 2023

According to Figure 7, G2 has the highest tendency of non-compliance in 2023. This group incurred a loss of S/. 160,414.29 due to non-compliance, which is equivalent to 8% of the annual penalty losses of the Mantaro Hydroelectric Plant.

E. Noncompliance and economic gains after modernization of the Speed regulator.

In 2024, the first week of March, the modernization of the G2 speed regulator was carried out, and from that date the greatest advantage of modernizing a speed regulator is reflected.

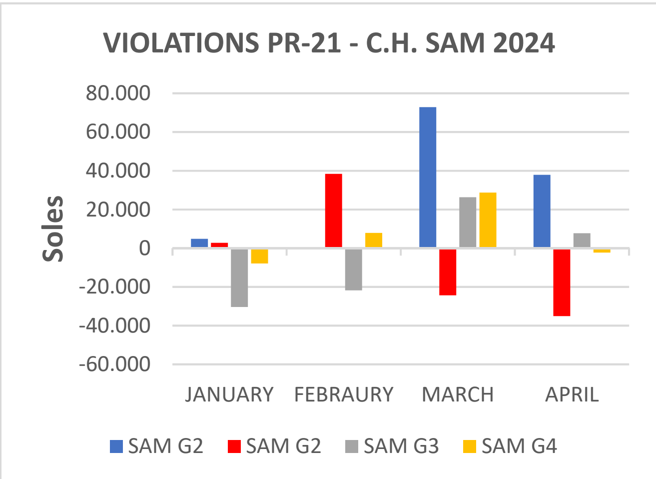

Fig. 8. Behavior of G1, G2, G3 and G4, based on the non-compliance with PR21 of 2024

According to what is illustrated in Figure 8, it is observed that G2 after the modernization of the speed regulator in the beginning of March 2024, the generating unit complies with the frequency drop in the SEIN and, as a result, stops incurring the penalties issued in the PR21 regulations.

IV. Discussion of Results

The main objective is to analyze the technical, operational, and economic benefits derived from the modernization of the speed regulator in the Mantaro hydroelectric power plant, in order to evaluate the feasibility and advisability of implementing this type of improvements in other hydroelectric power plants in the national electricity system. This general objective is based on the findings of various studies, such as [8], [9] y [10]; The 3 studies highlight the importance of optimizing the performance and efficiency of hydroelectric power plants.

The specific objective 1 of the research is to Evaluate the impact of the modernization of the speed regulator on the dynamic response of the Mantaro hydroelectric power plant in the face of disturbances in the frequency of the electrical system, this impact is visualized in Fig. 8. Behavior of G1, G2, G3 and G4, based on the non-compliance with PR21 of 2024 and in the same way it is justified in the findings reported in the study [8], where it is identified that frequency regulation is a key aspect for the efficient development of hydroelectric projects.

The specific objective 2 is to Analyze the impact of the modernization of the speed regulator on the operational efficiency and energy production of the Mantaro hydroelectric power plant according to a comparative of non-compliance in figures 6 and 8, verifying that after the modernization of the speed regulator, this penalty becomes profitable. This objective is supported in the article [9], that studies the feasibility of implementing more efficient technologies in energy generation systems.

The specific objective 3 is to Analyze the additional income obtained by meeting the primary frequency regulation performance standards established by the regulatory agency. This objective is supported by the findings of the study [10] which addresses the regulatory and economic problems associated with the operation of hydroelectric power plants in Peru, as reflected in Fig. 8, the generation group 2 stops incurring penalties and receives an economic benefit in the months of March and April, with an average gain of S/. 49,000.00 in just 2 months after the modernization.

The results obtained in the present research show that the modernization of the speed regulator in the Mantaro hydroelectric power plant has significant technical, operational and economic impacts. From a technical point of view, the modernization of the speed regulator improved the dynamic response of the plant to frequency disturbances, which is reflected in better compliance with the standards established by the regulatory agency. From an operational point of view, the modernization allowed increasing the efficiency and energy production of the plant, by avoiding penalties for non-compliance with primary frequency regulation. Finally, from an economic point of view, the improvement in technical and operational performance resulted in additional income for the plant, due to the collection of incentives for compliance with performance standards. Together, these findings support the feasibility and convenience of implementing this type of improvement in other hydroelectric power plants in the national electricity system, with the aim of optimizing their performance and contributing to the efficiency and sustainability of the electricity system.

V. CONCLUSIONES

- The results show that the modernization of the speed regulator of the Mantaro hydroelectric power plant significantly improved the dynamic response of generator unit G2 to disturbances in the frequency of the electrical system. This is evidenced by compliance with the primary frequency regulation performance standards set by the regulatory agency.
- It has been verified that the modernization of the speed regulator of the G2 generator unit of the Mantaro hydroelectric power plant had a positive impact on operational efficiency and energy production. This translates into higher economic revenues due to the reduction of penalties for non-compliance with frequency regulation regulations.
- The study results show that the modernization of the speed regulator of generator unit G2 at the Mantaro hydroelectric power plant generated significant additional revenue through compliance with primary frequency regulation performance standards. These additional revenues represent an important economic benefit for the hydroelectric power plant.

VI. RECOMMENDATIONS

- It is recommended to review the current regulatory framework to see the possibility of delegating primary frequency regulation to other power plants, in order to diversify the market for ancillary services in the Peruvian electrical system.
- It is recommended that the speed regulators of the hydroelectric power plants of the National Interconnected Electrical System be modernized gradually, prioritizing those generating units that have the greatest impact on primary frequency regulation.
- The regulatory agencies and the electricity system operator should establish more attractive economic incentives to promote the modernization of frequency regulation systems in hydroelectric power plants, given the benefits this generates for the stability and reliability of the electrical system.
- It is suggested to carry out similar studies in other hydroelectric power plants in the country to quantify the benefits of modernizing the frequency regulation systems, and use them as inputs for future regulatory and energy policy updates.
- It is recommended that the regulator incorporate more stringent requirements in the regulations regarding the performance of primary frequency regulation, in order to further incentivize the modernization of the control systems of the generating power plants.

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